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Impact of perennial pasture and tillage systems on carbon input and soil quality indicators

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ABSTRACT

Soil degradation associated with tillage is a major problem in Uruguayan agriculture. Either rotation of crops with pastures (ROT) or no-till (NT) cropping have been proposed as alternatives to minimize the impact of agriculture on soil quality. The combined impact on soil properties of ROT and NT has not been evaluated. In this study, we report results of the first 12 years of a long-term experiment established on a clay loam soil in western Uruguay. The objective was to determine the influence of conventional tillage (CT) and NT on systems under continuous cropping (CC, two crops per year) or ROT (3.5-year annual crops/2.5-year pastures). Soil samples taken at the beginning of the experiment in 1994 and in 2004 were analyzed for organic carbon (SOC), total organic carbon (TSOC) and total nitrogen content (STN), and for water-stable aggregation (WAS). Soil loss and erodibility indicators were studied using microrain simulator. With 12 years, the cumulative carbon (C) inputs of aboveground biomass were similar between tillage, but C input in CC was 50% higher than ROT. This difference was explained because 84% of the pastures dry matter was consumed by animals. Nevertheless we estimated a higher below ground biomass in ROT compared to CC systems (24.9 Mg ha^{-1} vs. 10.9 Mg ha^{-1}). NT presented 7% higher SOC than CT (0–18 cm) with no differences between rotation systems. While all treatments declined in STN during 12 years, ROT had 11% and 58% higher STN and WAS than CC systems, with a large impact of the pasture under CT. Runoff and erosion were minimized under NT in both rotations systems. Thus, including pastures in the rotation, or switching from CT to NT improved soil quality properties. The expected benefit of combining NT and ROT will likely require more years for the cumulative effect to be detectable in both C input and soil properties.

1. Introduction

Maintaining and improving soil organic carbon (SOC) content are important objectives for developing sustainable agricultural systems. Degradation of agricultural soils is a major concern in Uruguay. With the expansion of mechanized agriculture during the first half of 20th century, soils became severely degraded by continuous cropping (CC) with conventional tillage (CT) due to increased soil erosion and soil organic matter oxidation (Rasmussen and Collins, 1991; Carroll et al., 1997; Zheng et al., 2004). During the second half of 20th century two phases in the control of soil degradation were developed in Uruguay. Cropping systems changed from CC to annual crops in rotation with perennial pastures (ROT) using CT. Later, no-till (NT) was adopted as predominant soil management system (García-Préchac et al., 2004).

In Uruguay, Díaz-Roselló (1992) quantified a SOC loss of 25% after 28 years of CC using CT systems which agrees with findings in other zones of the world. Under crop–pasture rotation SOC increases during pasture phase and decreases in the crop phase, with no net change at the end of the 4-year crop–4-year sod-legume pasture. Most studies have demonstrated an increment of SOC after pastures and a continuous decline on continuous annual crops (Low et al., 1963; Greenland, 1971; Miglierina et al., 2000; Díaz-Zorita et al., 2002). Change in amount and distribution of C input particularly that from roots biomass, explains increase in SOC of soil under perennial grasses (Clement and Williams, 1964; Paustian et al., 1997; Haynes et al., 1991; Arshad et al., 2004; Hermle et al., 2008). Carbon input from perennial pasture is greater than estimates of standing root biomass since C enters the soil also from fine roots and rhizodeposits (Trujillo et al., 2006). The average shoot/root ratio has been estimated to be around 6.0 and 1.5 for annuals crops and pastures (legume + grass), respectively (Bolinder et al., 2007).

Haynes et al. (1991) reported that aggregate stability increases quickly during pasture phase, both due to a lack of tillage

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disturbance and the characteristic dense and fibrous root systems of perennial grasses. This effect stays if the perennial pasture remains in time, but is lost quickly if soil is tilled again.

No-tillage has been proposed as a strategy to mitigate SOC depletion by converting agriculture soils from CO_2 source to CO_2 sink. Several studies have reported that SOC is lower with CT when compared to NT systems. The reasons for such differences have been variously attributed to: quick residue decomposition, more oxidative environment and soil erosion, (Dalal, 1989; Havlin et al., 1990; Zheng et al., 2004). However the magnitude and direction of SOC changes vary with soil type, weather conditions, crop sequence, and quantity of stubble returned to soil (Janzen et al., 1998). Gains in SOC caused by improved soil management practices is likely finite, and depends on the initial SOC, potential net primary production and climate (Janzen et al., 1998). For Argentine conditions, Steinbach and Alvarez (2006) showed that 13 of 60 study cases had lower SOC with NT than CT systems. These authors found an increment of 15% in low initial SOC and losses of 5% in high initial SOC (less than 20 Mg ha^{-1} and more than 80 Mg ha^{-1} in 0–100 cm depth, respectively).

García-Préchac et al. (2004) reported a decrease of 50% in soil erosion rate where crop–pasture rotation changes from CT to NT systems. Gilley et al. (1997) showed that the superior erosion-resistance potential of NT compared with CT systems was correlated with maintenance of SOC level and mean weight diameter under NT systems.

Combining the benefits from rotating crops with pastures with NT could greatly increase the sustainability of agriculture and improve soil quality. The objective of this study was to quantify the effect of tillage (CT vs. NT) and rotation (CC vs. ROT) on some chemical and physical properties of agricultural soils in Uruguay. For this purpose we analyzed data on SOC and STN evolution, aggregate stability and soil erodibility from an experiment established in 1993.

2. Materials and methods

2.1. Site description

The experiment was located 10 km south of Paysandú (32°21′S and 58°02′W; 61 m elevation) in the northwest of Uruguay, which corresponds broadly with the eastern edge of the South American Pampas. The climate is meso-thermal sub-humid climate with a mean daily temperature of 25 and 13 °C for summer and winter, respectively, and annual precipitation of 1200 mm distributed on average uniformly within the year, but with large intra- and inter-annual variation. Both, excess water during winter (maximum in July, 60 mm) and water shortages during summer (maximum in January, 100-mm) are common.

Soil at the site is a fertile Typic Argiudol (Table 1) with a slope of about 1.0%. Between 1940 and 1970 the study site had been cultivated with continuous crops (a wheat-fallow rotation) under CT (inversion tillage plus several secondary operations). From 1970 until the beginning of the experiment in 1993, the experimental area was under crop–pasture rotation (3–3 years of pastures and crops) with CT.

Table 1
Surface (0–20 cm) characteristics of the experimental site where tillage systems with inclusion or not of pastures were evaluated in the long-term experiment in Paysandú, Uruguay at 1993.

Classification	Typic Argiudol
Texture	Clay loam
Clay (g kg^{-1})	290
Silt (g kg^{-1})	440
Sand (g kg^{-1})	270
Soil organic carbon (g kg^{-1})	30
pH	7.0
P content (mg kg^{-1})	15
K content (cmol kg^{-1})	1.9
Ca content (cmol kg^{-1})	27.7
Mg content (cmol kg^{-1})	2.4
Cation exchange capacity (cmol kg^{-1})	32.7

2.2. Site management

The long-term experiment was established in the fall of 1993 following a sod-legume pasture composed originally by birdsfoot trefoil (*Lotus corniculatus* L.), white clover (*Trifolium repens* L.) and tall fescue (*Festuca arundinacea* L.) which was gradually invaded by bermudagrass (*Cynodon dactylon* L.). The following crops were used in the rotation: wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and oat (*Avena sativa* L.) for winter crops and corn (*Zea mais* L.), sunflower (*Helianthus annus* L.), sorghum (*Sorghum bicolor* L. *Moench.*), and soybean (*Glycine max* (L.) Merr.) for summer crops. The cropping sequence is shown in Table 2.

Table 2
Crops evaluated in a combination of two tillage systems and two rotations (inclusion or not of pastures) in the long-term experiment in Paysandú, Uruguay (1993–2004).

Year	Continuous cropping (CC)		Crop–pasture rotation (ROT)	
	Winter	Summer	Winter	Summer
1993	Barley	Sorghum	Barley	Sorghum
1994	Wheat	Sunflower	Wheat	Sunflower
1995	Wheat	Sorghum	Wheat/pasture	Pasture
1996	–[a]	Corn	Pasture	Pasture
1997	Oat	Soybean	Pasture	Pasture
1998	–	Corn	–	Corn
1999	Wheat	–	Wheat	–
2000	Wheat	Soybean	Wheat	Soybean
2001	–	Sunflower	–	Sunflower
2002	Wheat	Soybean	Wheat/pasture	Pasture
2003	–	Sunflower	Pasture	Pasture
2004	Barley	Soybean	Pasture	Pasture

[a] Means fallow due to impossibility to plant for weather conditions.

Four treatments arranged in a randomized block design with three replications were evaluated from 1993 to 2006. These treatments included factorial combinations of two cropping systems (CC and ROT) and two tillage systems (CT and NT):

1. Continuous cropping with conventional tillage (CC_{CT}). Tillage included a combination of moldboard or chisel plow (depending on the year) to a depth of 20–25 cm followed by disking to a depth of 10–15 cm prior to winter crops. After winter crops harvest, the soil was tilled using disk harrow to a depth of 15–20 cm, followed by field cultivator to a depth of 10–15 cm and then, summer crop was seeded. Including planting, a minimum of three tillage operation were applied prior to each crop.
2. Continuous cropping with no-till (CC_{NT}). Same crops as CC_{CT}. Glyphosate was applied at the rate of 1.5–2.0 kg a.i. ha^{-1} depending on weed infestation and weather conditions.
3. Crop–pasture rotation with conventional tillage (ROT_{CT}). The rotation was 3.5-year crop–2.5-year pasture cycle; a system similar to that in operation since 1970, and using same tillage as CC_{CT}. The pasture was under sown together with the winter crop (in the same planting operation) in 1995 and 2002. The sod-legume pasture consisted of birdsfoot trefoil, white clover, and tall fescue.
4. Crop–pasture rotation with no-till (ROT_{NT}). The same tillage used in CC_{NT}. The rotation was the same used in conventional tillage (ROT_{CT}).

Pre- and post-emergent herbicides were applied in all treatments to control weeds as needed. Nutrients, insects and diseases were managed following recommendations of Agronomy Faculty. The experiment occupied approximately 2 ha with individual plots of 50 m × 10 m in size, thereby allowing the use of field-scale equipment for all operations.

2.3. Residue dry matter production from crop and pasture

The pasture was grazed an average of 7 times per year with about 15–25 steers of ~350 kg during 1 day in the six plots (3000 m^2) depending on dry matter availability. Grazing time was defined when forage availability $(FA) \geq 2.0$ Mg ha^{-1} dry basis. Immediately before and after the grazing period aboveground plant biomass was collected on three randomly selected 0.09 m^2. Forage was clipped at ground level in each plot, dried in a forced-air oven at 60 °C for 48 h, and weighed to determine FA and residual forage (RF).

Dry matter produced (DMP) and animal dry matter intake (AI) were estimated as:

$$\mathrm{DMP}(n) = \mathrm{FA}(n) - \mathrm{RF}(n-1) \qquad (1)$$

$$\mathrm{AI}(n) = \mathrm{FA}(n) - \mathrm{RF}(n) \qquad (2)$$

Residual dry matter (RDM) was calculated as:

$$\mathrm{RDM} = \sum \mathrm{DMP} - \sum \mathrm{AI} + \mathrm{RFe} + \mathrm{RG} \qquad (3)$$

where RFe = RF at the end of pasture phase; RG = DMP from the last grazing to total herbicide application date in $\mathrm{ROT_{NT}}$ or first tillage in $\mathrm{ROT_{CT}}$.

Below ground biomass (BGB) produced during each pasture phase was estimated according to algorithms developed by Gill et al. (2002):

$$\mathrm{BGB} = 0.8(\mathrm{AGB}) - 33.3(\mathrm{MAT} + 10) + 1.3 \qquad (4)$$

where AGB = above ground biomass (Mg ha^{-1}); MAT = means annual temperature (°C).

Grain yield on each plot was measured by harvesting the central 120 m^2 with a combined plot harvester and above ground crop residue dry matter from the average harvest index for each plot. Crop BGB was estimated using shoot/root ratio of 7.4 for wheat and barley, 5.2 for soybeans and sunflower and 5.6 for corn and grain sorghum as reported by Bolinder et al. (2007).

2.4. Soil organic carbon and total nitrogen content

Soil samples for organic carbon and total nitrogen (STN) were collected in January 1994 (6 months after initiation of the experiment) and June 2005. Ten samples taken at three different depths (0–6, 6–12, and 12–18 cm) were composited for each plot. Samples were lightly crushed and sieved through a 2 mm mesh. Soil organic carbon was determined using the Walkey and Black technique (Nelson and Sommers, 1982) and STN by the Kjeldahl semi-micromethod (Bremner and Mulvaney, 1982). Soil bulk density (BD) was determined by the core method (Blake and Hartge, 1986), with core dimensions of 46 mm diameter by 60 mm height. Core samples were taken at the same depths as SOC and STN determinations at the same time, 5 replicates per plot, dried to 105 °C and weighed. As was proposed by Ellert and Battany (1995), the effects of management on total SOC was clarified by eliminating the disparity attributed to unequal soil bulk density. As a consequence, total soil organic carbon (TSOC) was calculated in an identical or 'equivalent' mass soil within year, resulting in 1998 and 2160 Mg ha^{-1} for 1994 and 2005, respectively.

2.5. Wet aggregate stability

To evaluate wet aggregate stability (WAS) soil samples collected in June 2005 were processed using a wet sieving procedure of Yoder (1936) as modified by Kemper and Rosenau (1986). Three samples for the 0–10 cm layer were collected from each plot. Immediately after collection, aggregates between 4.5 and 9.5 mm were separated from the composite sample, by gently massaging large clouds to free aggregates of the preferred size. Moist aggregates (30 g) of between 4.5 and 9.5 mm were spread evenly on the uppermost sieve of a nest of 4.5, 2.8, 2.0, 1.0, 0.6 and 0.3 mm diameter. To avoid sudden rupture of the aggregates, the screens were lowered to wet the base of the topmost sieve to allow aggregates to become completely wet (10 min) by capillary. The water level in the shaking apparatus was adjusted so that aggregates on the uppermost sieve were just submerged on the highest point of the cycle. Samples were oscillated for 15 min at 40 strokes per minute with the amplitude of the action set at 8 cm. The soil remaining on every sieve at the end of the 15 min was transferred into a beaker and oven-dried at 105 °C for 48 h and then weighed. The strength of aggregates in water was calculated as mean weight diameter $(\mathrm{MWD}) = \Sigma(X_i W_i)$, where X is the average diameter of the openings of two consecutive sieves, and W the weight ratio of aggregates remained on the ith sieve. The multipliers used in our study after wet sieving were 7, 3.65, 2.4, 1.5, 0.8, and 0.45 mm for the sieves, respectively, and 0.15 mm for the remaining soil.

2.6. Infiltration and rainfall simulation measurements

Soil erodibility was measured in July 2005, which coincided with the first year of the pasture phase for the rotational treatments, using a portable microrainfall simulator developed by Kamphorst (1987). Drops are produced by means of water falling from reservoir trough 49 capillary tubes placed 40 cm above the soil surface. The rain simulator allows measuring the time to runoff, water runoff, and soil and carbon loss generated by a standardized rain shower on a plot with 1.1% average slope. This method gives relative values of infiltration and runoff from small plots and it is not providing absolutes rates of erosion and C losses in large areas. García Préchac et al. (1999) demonstrated a good correlation between soil erodibility (K) and soil losses collected using it. Prior to the application of simulated rain, soil samples were taken in the topsoil (0–10 cm), then oven-dried at 105 °C for 72 h to estimate gravimetric water content. No differences in the average gravimetric water content were found among treatments (average 0.32 g g^{-1}). During each measurement, time to start of runoff was recorded. The runoff plot of the rainfall simulator covered an area of 0.09 m^2 and was surrounded with a metal frame so that all runoff water could be collected at the lowest point using a bucket. Three random measurements per plot were performed. The simulated rainfall intensity was about 250 mm h^{-1} for 3 min. This intensity was needed to compensate for the short falling distance, in order to obtain a realistic kinetic energy of the raindrops. Infiltration (%) was determined as the difference between the application rate and runoff rate. The runoff samples collected during the rainfall simulation experiment were analyzed in the laboratory to determine both soil and soil carbon loss. Runoff samples were oven-dried at 105 °C to obtain soil loss expressed in kg m^{-2}. Runoff organic carbon was determined using the Walkey and Black technique expressed in g m^{-2} (Nelson and Sommers, 1982).

2.7. Statistical analysis

Treatment effects were evaluated using full factorial design with randomized block with the PROC MIXED procedure of the

Statistical Analysis System (SAS) (Littel et al., 1996). Replication and its interactions were considered random effects and treatments were considered fixed effects. Sampling depths were analyzed as a split in the design. Least square means comparisons were made using Fisher's protected least significant differences (LSD). A significance level of $P \leq 0.10$ was established a priori.

3. Results and discussion

3.1. Residue dry matter production from crop and pasture

As we expected, no difference was detected between rotations systems on crop residue production during phase I, since all treatments were installed after old pasture (14.9 Mg ha^{-1} vs. 15.7 Mg ha^{-1} for CC and ROT, respectively) (Table 3). There was a trend toward higher crop residue DM using CT compared to NT in the phase I (15.9 Mg ha^{-1} vs. 14.7 Mg ha^{-1}, $P = 0.16$). Additionally, no significant differences were found between tillage systems in phase II (1996–1998). After the first pasture (phase III), higher crop residues DM was obtained under ROT systems ($P \leq 0.10$). There were no differences between tillage systems in phases III and IV for crop residues DM. After 12 years of treatments, within continuous cropping or crop pasture rotations, the aboveground carbon added as crop residues DM was not modified by tillage system (67.4 Mg ha^{-1} vs. 69.7 Mg ha^{-1} and 40.8 Mg ha^{-1} vs. 41.1 Mg ha^{-1} 1 for CT and NT, respectively).

Table 4 shows the pasture dry matter production during the two pasture phases. There were no significant differences between tillage systems on DMP and AI, neither phase II nor phase IV. However, in phase II, CT had higher above ground RDM than NT system (2.9 Mg ha^{-1} vs. 1.6 Mg ha^{-1}, respectively, $P \leq 0.05$) determined by high infestation of *Cynodon dactylon* at the end of the pasture phase. Averaged over tillage systems and phases, around 84% (21.4/25.6 Mg ha^{-1}) of the pasture DMP was consumed by the animals, and only 4.2 Mg ha^{-1} was left as above ground RDM in 5 years (adding phases II and VI).

After 12 years of treatments, as was mentioned in Table 3, averaged over tillage system, above ground crop residue was 68.6 Mg ha^{-1} and 41.0 Mg ha^{-1} for CC and ROT, respectively. Considering above ground pasture RDM and crop residue in the ROT system, the total above ground DM input was 45.2 Mg ha^{-1} (41.0 + 4.2 Mg ha^{-1} for crops and pasture dry matter, respectively) averaged over tillage systems. As shown Table 5, the difference was explained by higher above ground crops residue in CC than above ground pasture residue in ROT systems during phases II and IV. While CC produced 34.0 Mg ha^{-1} of crop residue during phase II and IV (Table 5), ROT system produced 25.6 Mg ha^{-1} of above ground pasture, but 21.4 Mg ha^{-1} (84%) was consumed by the animals (Table 4). This represented 66% lower above-ground biomass input in ROT compared to CC systems (41.0 + 4.2 Mg ha^{-1} vs. 68.6 Mg ha^{-1}, respectively). However, recycling through the animal excreta was not accounted in the estimated C input. Vu et al. (2008) developed prediction equations for estimating the daily amount of feces and C excretion from pigs based on diet composition and AI. Considering fiber content of a mixed pasture and total AI estimated over tillage systems and phases (21.4 Mg ha^{-1}), above ground pasture RDM could be increased by about 6.0 Mg ha^{-1}, for a total residue input of 76.1 Mg ha^{-1} (70.1 + 6.0 for total residue and animal excreta, respectively).

Table 3
Above ground crop residue dry matter estimated (Mg ha^{-1}) in each rotation phases as influenced by rotation and tillage system in the long-term experiment in Paysandú, Uruguay (1993–2004).

Phases	Continuous cropping (CC)		Crop–pasture rotation (ROT)	
	CT[a]	NT[b]	CT	NT
I (1993–1995)	15.4 a	14.4 a	16.4 a	15.0 a
Means	14.9 a		15.7 a	
II (1996–1998)	19.4 a	18.5 a	–[c]	–
III (1999–2002)	18.7 a	20.7 a	24.4 a	26.1 a
Means	19.7 b		25.3 a	
IV (2002–2004)	13.9 a	16.1 a	–	–
Total crop residue (Mg ha^{-1})	67.4 a	69.7 a	40.8 b	41.1 b

[a] Conventional tillage.
[b] No-till.
[c] Since are not crops in period II and IV, the dry matter forages are not consider.

Table 4
Production, animal intake and residual above ground pasture dry matter measured (Mg ha^{-1}) in two phases as influenced by tillage system in the long-term experiment in Paysandú, Uruguay (1993–2004).

Pasture dry matter	Phase II (1996–1998)		Phase IV (2002–2004)		Total II + IV (1996–2004)	
	CT[a]	NT[b]	CT	NT	CT	NT
Produced	11.3 a	11.2 a	13.6 a	15.1 a	24.9 a	26.3 a
Animal intake	8.4 a	9.6 a	11.8 a	13.0 a	20.2 a	22.6 a
Residual above ground	2.9 a	1.6 b	1.8 a	2.1 a	4.7 a	3.7 a

[a] Conventional tillage.
[b] No-till.

We estimated that ROT systems produced 128% more pasture and crops BGB than CC systems (24.9 and 10.9 Mg ha^{-1}, respectively). Analyzing only phases II and IV, the pasture produced more BGB than the crops (18.4 Mg ha^{-1} vs. 5.4 Mg ha^{-1}, 1, respectively). It has been suggested that crop pasture rotation has a strong potential to mitigate the SOC depletion by sequestering C in the soil (Miglierina et al., 2000; Díaz-Zorita et al., 2002). Our study strongly suggests that BGB is an important component of this mitigation potential. The total DM input estimate (adding below and above ground) after 12 years was 13% higher in CC than ROT systems (79.5 and 70.1 Mg ha^{-1}, respectively), however as we mentioned before, 86% was above ground in the CC systems, and only 64% was for ROT systems.

3.2. Soil organic carbon and total nitrogen content

Soil TN, SOC, BD, and TSOC resulting from combinations of tillage systems and inclusion or not of perennial pastures averaged over the 0–18 cm depth in 1994 and 2005 are presented in Table 6. Only tillage system effects within crop–pasture rotation are presented in 1994 because continuous cropping was not yet implemented. Six months after started the experiment (January 1994), there were no significant differences among tillage systems for SOC, TSOC and STN. At the beginning of the experiment BD was significantly higher in ROT$_{NT}$ than ROT$_{CT}$ (1.26 g cm^{-3} vs. 1.11 g cm^{-3}, respectively, $P = 0.08$).

With 12 years after initiation of the experiment, SOC was affected by tillage systems (Table 6). No-till had 7% higher SOC compared to CT (24.4 g kg^{-1} vs. 22.8 g kg^{-1}, respectively, $P = 0.08$) and 8% higher TSOC (52.6 Mg ha^{-1} vs. 49.0 Mg ha^{-1}, $P = 0.09$).

Several studies of tillage systems have reported that SOC is lower with CT than NT systems (Dalal, 1989; Havlin et al., 1990; Zheng et al., 2004). However some studies have reported little or no difference among tillage systems (Campbell et al., 1998). Soil organic C tendency is a balance between C inputs (above and below residue dry matter) and C losses (residue decomposition, oxidation process, and erosion). Since total residue dry matter input among tillage systems was similar among treatments (Tables 3 and 4), we hypothesized that the small difference in SOC between treatments could be explained by differences in C losses, either by oxidation or erosion (Rasmussen and Collins, 1991; Zheng et al., 2004). For this

Table 5

Below ground biomass, crop residue, and residual above ground pasture estimates as affected by cropping systems (Mg ha^{-1}) in all period under study in the long-term experiment in Paysandú, Uruguay (1993–2004) (averaged over tillage systems).

Dry matter	Phases									
	I		II		III		VI		Total	
	CC[a]	ROT[b]	CC	ROT	CC	ROT	CC	ROT	CC	ROT
Crops										
Below ground biomass	2.4	2.5	3.0	–[c]	3.1	4.0	2.4	–	10.9	6.5
Crop residue (above ground)	14.9	15.7	19.0	–	19.7	25.3	15.0	–	68.6	41.0
Pastures										
Below ground biomass	–[d]	–	–	8.0	–	–	–	10.4	–	18.4
Pasture residue (above ground)	–	–	–	2.2	–	–	–	2.0	–	4.2
Total residue	17.3	18.2	22.0	10.2	22.8	29.3	17.4	12.4	79.5	70.1

[a] Continuous cropping.

[b] Crop pasture rotation.

[c] Since there are not crops in phase II and IV, the dry matter in crop pasture rotations are not consider.

[d] Since there are not pasture in all phases, the pasture dry matter is not consider.

Table 6

Soil total nitrogen (STN), soil organic carbon (SOC), and bulk density (BD) at 0–18-cm depth and total soil organic carbon (TSOC) at equivalent mass at two soil sampling dates in response of tillage type and inclusion or not of pastures in the long-term experiment in Paysandú, Uruguay (1993–2004).

Treatments[a]	Year							
	1994				2005			
	STN (g kg^{-1})	SOC (g kg^{-1})	BD (g cm^{-3})	TSOC[b] (Mg ha^{-1})	STN (g kg^{-1})	SOC (g kg^{-1})	BD (g cm^{-3})	TSOC[c] (Mg ha^{-1})
1. CC_{CT}	–[d]	–	–	–	1.63	22.1	1.20	47.3
2. CC_{NT}	–	–	–	–	1.89	24.3	1.20	51.8
3. ROT_{CT}	2.02	22.0	1.11	44.0	1.87	23.5	1.20	50.6
4. ROT_{NT}	2.17	22.2	1.26	45.9	2.03	24.4	1.25	53.4
$LSD_{0.10}$	*ns*	*ns*	*0.08*	*ns*	*0.17*	*ns*	*ns*	*ns*
Contrasts								
CT (1,3)	–	–	–	–	1.75	22.8	1.20	49.0
vs. NT (2,4)	–	–	–	–	1.96	24.4	1.23	52.6
$P \leq$					*0.03*	*0.08*	*0.14*	*0.09*
CC (1,2)	–	–	–	–	1.76	23.2	1.20	49.6
vs. ROT (3,4)	–	–	–	–	1.95	24.0	1.23	52.0
$P \leq$					*0.04*	*0.39*	*0.15*	*0.24*
Initial[c]		*30.3*	*1.23*	*65.5*				

[a] CC_{CT} = continuous cropping with conventional tillage; CC_{NT} = continuous cropping with no-till; ROT_{CT} = crop–pasture rotation with conventional tillage; ROT_{NT} = crop–pasture rotation with no-till.

[b] Equivalent soil mass (1998 Mg ha^{-1}).

[c] Equivalent soil mass (2160 Mg ha^{-1}).

[d] Since the treatments started in July 1993, continuous cropping systems are not consider.

study, CO_2 effluxes might have been reduced under CT systems. Because CT system was realized using a minimal number of tillage operations, annual double cropping system (1.7 crop year^{-1}), stubble was retained in plots, and there were only five long fallow periods in 12 years.

The inclusion of grazed perennial pasture in the crop sequence did not affect SOC (23.2 g kg^{-1} vs. 24.0 g kg^{-1} for CC and ROT, respectively). Similar results were found by Díaz-Zorita et al. (2002) that showed an interaction between tillage and rotation systems, where SOC level depended on perennial pasture inclusion when annual crops are seeded with CT, but not with NT system.

The lack of differences between rotations may be due to: 1. relatively low pasture above ground dry matter limited pasture BGB (Fisher et al., 1994; Abril and Bucher, 2001). 2. More than 85% of pasture DMP was consumed by the animals resulting in a very low pasture RDM. 3. Relatively high initial SOC that limited changes in the short term (Janzen et al., 1998). 4. Only 5 of 12 years the pasture was present in the treatment, leading to a low impact on SOC.

In contrast, above + below ground C inputs were 13% higher in CC than ROT systems (Table 5). Nevertheless this did not reflect in higher SOC. These results could be explained by C recycling through the animal excreta was not accounted (estimated in around 6.0 Mg ha^{-1} of dry matter). Two additional reasons could be: 1. More C losses from above ground crop residue in CC compared to ROT systems. 2. More C input from BGB in ROT (Table 5) compared to CC systems resulting in higher SOC due to a higher C humification than C from above ground residue (Liang et al., 2002). Therefore grazing directly on pasture would have much greater potential to sequester SOC than CC systems (Johnson et al., 2007).

Janzen et al. (1998) estimated a gain in total SOC of about 0.6 Mg ha^{-1} y^{-1} or less within a decade by adoption of improved practices, like conservation tillage, intensification cropping systems, improved crop nutrition and perennial pastures in Canadian prairies. Previous estimates of the effect of changing from CT to NT systems on SOC sequestration rate ranged from 0.33 to 0.48 Mg C ha^{-1} year^{-1} (Six et al., 2002; West and Post, 2002). Our results agree with results mentioned before, where TSOC increased 0.30 Mg ha^{-1} year^{-1} averaged across CC and ROT systems, after 12 years ($P = 0.09$).

The value of STN is the balance among input (principally N fertilization and N fixation by legume but also N fixation from non-symbiotic bacteria and N deposition) and losses (soil erosion, N removal with grain harvest, N removed by animals, denitrification, ammonia volatilization and percolation). The tillage or rotation system effects on STN in 2005 analysis were different than those of SOC. Soil total N decreased from initial values determined in 1994 within the 0–18-cm depth in all systems evaluated, being the greatest in CC_{CT} (Table 6). After 12 years, CC_{CT} had significantly lower STN than other treatments in 2005 (1.63 g kg^{-1} vs. 1.93 g kg^{-1} for CC_{CT} and averaged over three tillage × rotation systems mean, $P = 0.06$). The combined effect of CT and CC systems has been previously reported to reduce STN (Heenan et al., 2004). With CC systems, we detected a decrease in STN of 10% compared to ROT in 2005. However, N losses from the systems were mitigated by ROT by 56% compared to CC (2.10–1.95 and 2.10–1.76 g kg^{-1}for 1994 and 2005, respectively, averaged over tillage systems).

Nevertheless, ROT systems with or without tillage could not maintain the STN value measured at the beginning of the study. These results differ from the study by Morón (2003) who found in a similar soil type and rotation system but using ungrazed pastures (crop pasture rotation with CT) a small gain on STN after 40 years. Díaz-Roselló (1992) estimated a 0.125 Mg ha^{-1} year^{-1} of N gain in the first 20 cm depth by legume fixation in the same experiment (30 kg N Mg^{-1} DM legume). In our study, the total legume DM produced was 14.7 Mg ha^{-1} in 5 years (data not shown), equivalent to 0.09 Mg N ha^{-1} year^{-1} of N fixation. The contradictory results between these two experiments would not be the legume DM but the pasture management. While in the Morón (2003) study, pastures were ungrazed in our study pastures were grazed with cows that removed 84% of the pasture DM produced as we mentioned before (Tables 4 and 5).

Although no significant changes in C:N ratio were recorded in 2005 (data not shown), there was a tendency for a lower C:N ratio using ROT than CC (12.3 vs. 13.2, respectively, $P = 0.11$). This lower ratio would indicate more potential mineralizable organic N than CC. This could lead to increased crop demand for N in the CC compared to ROT (Franzluebbers, 2005).

A significant treatment × depth interaction was obtained for SOC in both years (Table 7). Significant stratification of SOC occurred only 6 months after establishment of the experiment. Conventional tillage had lower stratification ratio compared to NT systems (0–6/12–18 cm ratio = 1.13 vs. 1.35, respectively). After 12 years of the experiment, the stratification was similar in CT and NT systems as in 1994 (0–6/12–18 cm ratio = 1.18 and 1.35, respectively, averaged over CC and ROT). High initial stratification ratios due to old pasture at the beginning of the experiment (7 years old) could explain that NT only kept the stratification ratio. These results confirm early finding of Franzluebbers (2002) that most of the impact of NT is observed in surface soil. Within NT systems, there was no difference between the two rotation systems (CC and ROT). However, there was a consistent trend toward higher SOC content in the first 0–6 cm in CC compared to ROT (30.0 g kg^{-1} vs. 27.7 g kg^{-1}, respectively). As was mentioned before, CC produced more dry matter input compared to ROT above ground residues (68.6 Mg ha^{-1} vs. 45.2 Mg ha^{-1}, respectively, Table 5). However, in the following depth (6–12 cm), the trend was for greater SOC under ROT than CC (24.2 g kg^{-1} vs. 21.9 g kg^{-1}, respectively). This could indicate the greater capacity to increase SOC at depth from the pasture BGB on ROT compared to CC systems. Within CT, the inclusion of pasture increased significantly the SOC in the first 0–6 cm depth (26.7 g kg^{-1} vs. 23.2 g kg^{-1} for ROT and CC, respectively), without difference in others depths.

Comparing tillage systems in continuous crops (CC_{NT} vs. CC_{CT}), the NT system had greater SOC than CT only at the shallowest depth (30.0 g kg^{-1} vs. 23.2 g kg^{-1}, respectively). However, some authors have reported higher SOC contents at deeper layers under CT compared to NT due to residue incorporations by burying (Angers and Eriksen-Hamel, 2008; Blanco-Canqui and Lal, 2008). Thus, we hypothesize that the same value of SOC deeper in the soil profile using CT or NT was due to the same C input produced in both treatments (Table 3). Within ROT systems, there was no difference in SOC content for any profile under study between tillage systems.

3.3. Wet aggregate stability

Significant differences in water stable aggregation were detected among the four treatments. Mean weight diameter (MWD) calculated after wet sieving was significant for rotation, tillage systems and these interaction. The use of pasture rotations increased MWD by 140% compared to CC_{CT}. With NT, the beneficial effect of pasture to improve MWD was only 24% (Fig. 1). Across cropping systems, NT had greater MWD than CT (2.52 mm vs. 1.55 mm for NT and CT, respectively), but the effect was greatest in continuous cropping systems (2.24 mm vs. 0.91 mm for NT and CT, respectively). This was caused by a stronger pasture effect in CT than in NT systems, as mentioned before. Changes in aggregate stability with NT have been reported under different whether conditions (Dalal, 1989; Beare et al., 1994). Investigation by Haynes et al. (1991) indicated the strong influence of mixed cropping rotation on SOC and water stable aggregation. Soil aggregate stability has been shown to increase rapidly after perennial grasses both due to a lack of tillage disturbance and to characteristics of grass root systems (Paustian et al., 1997). In our study, perennial pasture in NT systems resulted in the highest soil

Table 7
Soil organic carbon (SOC) and total nitrogen (STN) at two soil sampling dates in response of tillage type and inclusion or not of pastures at three different depths in the long-term experiment in Paysandú, Uruguay (1993–2004).

Sampling date	Depth	Treatments[a]							
		SOC				STN			
		CC_{CT} (g kg^{-1})	CC_{NT} (g kg^{-1})	ROT_{CT} (g kg^{-1})	ROT_{NT} (g kg^{-1})	CC_{CT} (g kg^{-1})	CC_{NT} (g kg^{-1})	ROT_{CT} (g kg^{-1})	ROT_{NT} (g kg^{-1})
January 1994	0–6	–[b]	–	23.6	26.1	–	–	2.10	2.60
	6–12	–	–	21.6	21.2	–	–	2.05	2.00
	12–18	–	–	20.8	19.4	–	–	1.90	2.05
	$\text{LSD}_{(0.10)}$ (treatment × depth)		4.4				0.20		
December 2005	0–6	23.2	30.0	26.7	27.7	1.76	2.25	2.08	2.20
	6–12	22.2	21.9	22.4	24.2	1.61	1.76	1.82	1.97
	12–18	21.0	21.1	21.3	21.4	1.53	1.65	1.71	1.93
	$\text{LSD}_{(0.10)}$ (treatment × depth)		2.5				ns		

[a] CC_{CT} = continuous cropping with conventional tillage; CC_{NT} = continuous cropping with no-till; ROT_{CT} = crop–pasture rotation with conventional tillage; ROT_{NT} = crop–pasture rotation with no-till.

[b] Since the treatments started in July 1993, continuous cropping with or without tillage are not consider.

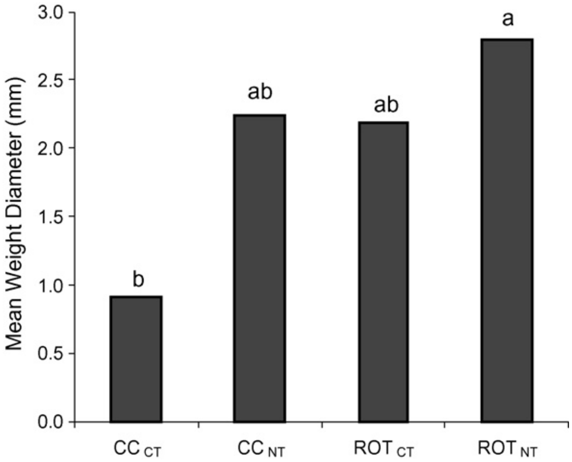

Fig. 1. Mean weight diameter in the surface 0–10 cm layer as affected by a combination of two tillage systems and two rotations (inclusion or not of pastures) in the long-term experiment in Paysandú, Uruguay (1993–2005). Histograms followed by a different superscript letter are significantly different ($P \leq 0.01$) (CC_{CT} is continuous cropping with conventional tillage, CC_{NT} is continuous cropping with no-till, ROT_{CT} is crop–pasture rotation with conventional, and ROT_{NT} is crop–pasture rotation with no-till).

aggregate stability with an average of seven grazing events per year during both pasture periods. Li et al. (2007) stated an intensive but short duration grazing could promote SOC and soil aggregate stability conservation compared with continuous and intensive grazing or cropping systems. Chan and Heenan (1999) stated that the stability of macro-aggregates is simply transitory and is extremely susceptible to agricultural management practices as a result of fragile stabilizing agents involved (fungal hyphae and bacterial products), as described by Tisdall and Oades (1982) and Oades (1984). These stabilizing agents determine the higher soil aggregate stability and explain both the rapid increase in MWD and SOC during pasture phase and its loss during the first and second crop after cultivation (Díaz-Roselló, 1992). This suggests that improved soil aggregate stability achieved at the end of the pasture period could disappear faster with conversion to cropping with CT than with NT.

3.4. Runoff and soil erosion risk

In Uruguay, rainfall amount and its distribution together with soil characteristics determine high soil water erosion. In this region, two main strategies have been developed to reduce soil erosion in annual cropping systems: 1. including perennial pasture within rotation or 2. including NT in CC systems. Results obtained using a microrainfall simulator during fallow period previous to wheat seeding are shown in Fig. 2. The lowest time to water runoff start was obtained in both CT systems followed by CC_{NT} and then by ROT_{NT} (Fig. 2A). No-till systems had 100% soil covered by residue, which delayed 72% by the start of runoff compared to CT systems (30.3 s vs. 108.2 s; $P = 0.001$). During fallow periods CT systems left soil surface uncovered and water runoff was stimulated (Meyer et al., 1970). For water runoff, tillage system was the most important factor (35 and 11% for CT and NT systems, respectively; $P = 0.0001$, Fig. 2B). Additionally, when the pasture was included, there was a significant effect on water runoff (29% vs. 17% for ROT and CC, respectively; $P = 0.0009$). Therefore, the best management practice to avoid soil erosion through decrease water runoff was to include pasture in the rotation in conjunction with NT.

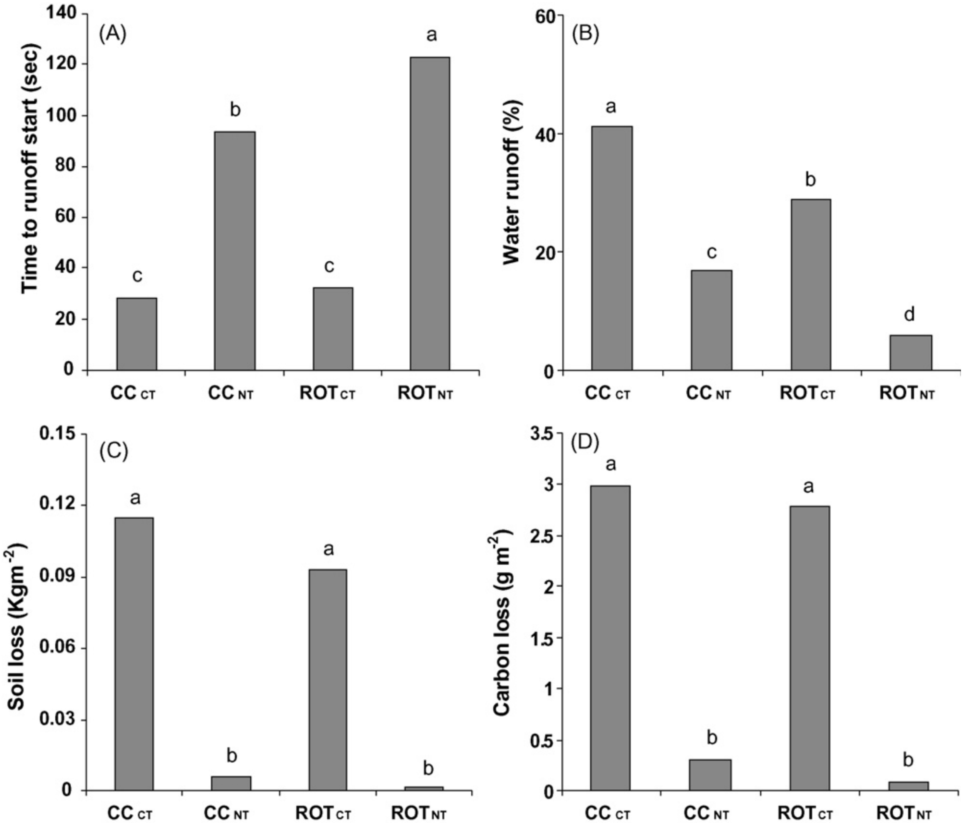

Fig. 2. Time to runoff (A), water runoff (B), soil loss (C), and carbon loss (D) as affected by a combination of two tillage systems and two rotations (inclusion or not of pastures) in the long-term experiment in Paysandú, Uruguay (1993–2004). Histograms followed by a different superscript letter are significantly different ($P \leq 0.010$) (CC_{CT} is continuous cropping with conventional tillage, CC_{NT} is continuous cropping with no-till, ROT_{CT} is crop–pasture rotation with conventional, and ROT_{NT} is crop–pasture rotation with no-till).

No-till systems with or without pasture had very low soil and carbon losses (Fig. 2C, D). These results agree with Zheng et al. (2004) who determined that CT runoff rates were from 1.7 to 2.9 times greater than those from NT systems. They summarized results from literature providing information about comparisons of runoff and soil loss under CT and NT systems. The averaged results were that NT caused approximately 25% decrease in runoff compared with CT systems. Raindrop impact on bare soil causes aggregate breakdown and more transportable particles and micro-aggregates. These particles can slow infiltration rate to produce increased runoff and soil erosion. As was discussed, CC_{NT} and ROT_{NT} improved aggregate stability, an important soil physical property associated with low water runoff. Franzluebbers (2002) proposed the stratification ratio of SOC as a simple diagnostic tool to identify land management strategies that improve soil water properties. In our study, negative consequence of CC_{CT} on MWD and surface-SOC would explain both, low time to runoff start and poor water infiltration. As we discussed previously, ROT_{CT} resulted in similar time of runoff start as CC_{CT} (30.3 s), but worst water runoff proportion (42 and 30% for CC_{CT} and ROT_{CT}, respectively; $P = 0.0009$). This could be explained by inadequate soil surface residue cover but better MDW. Although water runoff was measured in microplots (0.09 m^2), our results agree with the literature with larger plots. McGregor et al. (1999) determined that runoff from NT history plots (similar to pasture period in our study) was 11–35% less than from continuous CT history, due to the cumulative effects of cropping history. Gilley et al. (1997) showed that the superior erosion-resistance potential of NT compared with CT systems was related to soil organic matter and MWD. Our results indicate that NT systems were successful to reduce water runoff and, as consequence, improve water infiltration and reduced risk of losses of soil and SOC associated with water erosion. However, NT system in combination with crop–pasture rotation (ROT_{NT}) had an additional positive effect on water runoff control but not on soil and SOC losses.

4. Conclusions

This study showed that after 12 years, NT had 7% higher SOC compared to CT (24.4 g kg^{-1} vs. 22.8 g kg^{-1}, respectively, $P = 0.08$) and 8% higher TSOC in the 0–18 cm depth (52.6 Mg ha^{-1} vs. 49.0 Mg ha^{-1}, $P = 0.09$). Since total residue dry matter input between tillage systems were similar, we hypothesized that the difference on SOC between tillage systems could be explained by C losses, either by oxidation or erosion. The inclusion of grazed perennial pasture did not affect either SOC or TSOC. Above ground total C input in CC was 52% higher than ROT (68.6 Mg ha^{-1} vs. 45.2 Mg ha^{-1}, respectively) because 84% of the pastures dry matter was consumed by animals (21.4 Mg ha^{-1}). However, pasture systems recycle C by animal excreta and we estimated higher below ground biomass (24.9 Mg ha^{-1}) in these treatments compared to CC (10.9 Mg ha^{-1}).

Total soil N declined with time in all treatments, but depletion was mitigated by ROT systems. This result disagrees with many previous studies that had shown an increase in STN using legume, although in ungrazed systems. It was not possible to know the total amount of soil and SOC lost from each system. However results obtained with a small rainfall simulator indicated that soil and SOC lost from NT would be the lowest when crops and pasture are integrated in long time. These effects were associated to higher WAS and less water runoff. In the long term, crop–pasture rotations under NT would also be a way for diversifying production, improving soil quality and C inputs in the subsoil while providing flexibility and minimizing exposure to market swings in commodity prices.

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References

Abril, A., Bucher, E.H., 2001. Overgrazing and soil carbon dynamics in the western Chaco of Argentina. Appl. Soil Ecol. 16, 243–249.

Angers, D.A., Eriksen-Hamel, N.S., 2008. Full-inversion tillage and organic carbon distribution in soil profiles: a meta-analysis. Soil Sci. Soc. Am. J. 72, 1370–1374.

Arshad, M.A., Franzluebbers, A.J., Azooz, R.H., 2004. Surface-soil structural properties under grass and cereal production on a Mollic Cyroboralf in Canada. Soil Till. Res. 77, 15–23.

Beare, M.H., Cabrera, M.L., Hendrix, P.F., Coleman, D.C., 1994. Aggregated-protected and unprotected pools of organic matter in conventional tillage and no-tillage soils. Soil Sci. Soc. Am. J. 58, 787–795.

Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Klute, A. (Ed.), Methods of Soil Analysis. Part 1. Agron. Monogr. 9. 2nd ed. ASA and SSSA, Madison, WI, pp. 363–374.

Blanco-Canqui, H., Lal, R., 2008. No-tillage and soil-profile carbon sequestration: an on-farm assessment. Soil Sci. Soc. Am. J. 72, 693–701.

Bolinder, M.A., Janzen, H.H., Gregorich, E.G., Angers, 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. Agric. Ecosyst. Environ. 118 (1–4), 29–42.

Bremner, J.M., Mulvaney, C.S., 1982. Nitrogen total. In: Page, A.L, Miller, D.R. (Eds.), Methods of Soil Analysis II. Chemical and Micro-biological Properties. American Society of Agronomy, Madison, WI, pp. 595–624.

Campbell, C.A., McConkey, B.G., Biederbeck, V.O., Zentner, R.P., Curtin, D., Peru, M.R., 1998. Long-term effects of tillage and fallow-frequency on soil quality attributes in a clay soil in semiarid southwestern Saskatchewan. Soil Till. Res. 46, 135–144.

Carroll, C., Halpin, M., Burger, P., Bell, K., Sallaway, M.M., Yule, D.F., 1997. The effect of crop type, crop rotation, and tillage practice on runoff and soil loss on a vertisol in central Queensland. Aust. J. Soil Res. 35, 925–939.

Chan, K.Y., Heenan, D.P., 1999. The influence of crop rotation on soil structure and soil physical properties under conventional tillage. Soil Till. Res. 37, 113–125.

Clement, C.R., Williams, T.E., 1964. Leys and soil organic matter. I. The accumulation of organic carbon in soil under different leys. J. Agric. Sci. 63, 377–401.

Dalal, R.C., 1989. Long-term effects of no-tillage, crop residue, and nitrogen application on properties of a vertisol. Soil Sci. Soc. Am. J. 53, 1511–1515.

Díaz-Roselló, R.M., 1992. Evolución de la materia orgánica en rotaciones de cultivos con pasturas.(Organic matter evolution in crops and pastures rotations). Revista. INIA-Uruguay Inv. Agr. 1 (I), 103–110.

Díaz-Zorita, M., Duarte, G.A., Grove, J.H., 2002. A review of no-till systems and soil management for sustainable crop production in the subhumid and semiarid Pampas of Argentina. Soil Till. Res. 65, 1–18.

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

Fisher, M.J., Rao, I.M., Ayarza, M.A., Lascano, C.E., Sanz, J.I., Thomas, R.J., Vera, R.R., 1994. Carbon storage by introduced deep-rooted grasses in the South American savannas. Nature 371, 236–238.

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. Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA. Soil Till. Res. 83, 120–147.

García Préchac, F., Clérici, C., Terra, J.A., 1999. Avances con USLE-RUSLE para estimar erosión y pérdida de productividad en Uruguay. In Comisión VIII del 14° Cong. Latinoamericano de la Ciencia del Suelo, Pucón, Chile, en CD-ROM, 835 pp.

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

Gill, R.A., Kelly, R.H., Parton, W.J., Day, K.A., Jackson, R.B., Morgan, J.A., Scurlock, J.M.O., Tieszen, L.L., Castle, J.V., Ojima, D.S., Zhang, X.S., 2002. Using simple environmental variables to estimate belowground productivity in grasslands. Global Ecol. Biogeogr. 11, 79–86.

Gilley, J.E., Doran, J.W., Karlen, D.L., Kaspar, T.C., 1997. Runoff, erosion and soil quality characteristics of a former Conservation Reserve Program site. J. Soil Water Conserv. 52, 189–193.

Greenland, D.J., 1971. Changes in the nitrogen status and physical conditions of soils under pastures, with special reference to the maintenance of the fertility of Australian soils used for growing wheat. Soils Fertilizer 34, 237–251.

Havlin, J.L., Kissel, D.E., Maddux, L.D., Claassen, M.M., Long, J.H., 1990. Crop rotation and tillage effects on soil organic carbon and nitrogen. Soil Sci. Soc. Am. J. 54, 448–452.

Haynes, R.J., Swift, R.S., Stephen, R.C., 1991. Influence of mixed cropping rotations (pasture arable) on organic matter content, water stable aggregations and clod porosity in a group of soils. Soil Till. Res. 19, 77–87.

Heenan, D.P., Chan, K.Y., Knight, P.G., 2004. Long-term impact of rotations, tillage and stubble management of the loss of soil organic carbon and nitrogen from a Chromic Luvisol. Soil Till. Res. 76, 59–68.

Hermle, S., Anken, T., Leifeld, J., Weisskopf, P., 2008. The effect of the tillage system on soil organic carbon content under moist, cold-temperate conditions. Soil Till. Res. 98, 94–105.

Janzen, H.H., Campbell, C.A., Izaurralde, R.C., Ellert, B.H., Juma, N., McGill, W.B., Zenter, R.P., 1998. Management effects on soil carbon storage on the Canadian prairies. Soil Till. Res. 47, 181–195.

Johnson, J.M.-F., Franzluebbers, A.J., Weyers, S.L., Reicosky, D.C., 2007. Agricultural opportunities to mitigate greenhouse gas emissions. Environ. Pollut. 150, 107–124.

Kamphorst, A., 1987. A small rainfall simulator for the determination of soil erodibility. Neth. J. Agric. Sci. 35, 407–415.

Kemper, W.D., Rosenau, R.C., 1986. Aggregate stability and size distribution. In: Klute, A. (Ed.), Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods. Agronomy 9. 2nd ed. American Society of Agronomy, Madison, WI, pp. 425–442.

Li, X.G., Wang, Z.F., Ma, Q.F., Li, F.M., 2007. Crop cultivation and intensive grazing affect organic C pools and aggregate stability in arid grassland soil. Soil Till. Res. 95, 172–181.

Liang, B.C., Wangb, X.L., Mab, B.L., 2002. Maize root-induced change in soil organic carbon pools. Soil Sci. Soc. Am. J. 66, 845–847.

Littel, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D., 1996. SAS System for Mixed Models. SAS Inst., Cary, NC, pp. 31–86.

Low, A.J., Piper, F.J., Roberts, P., 1963. Soil changes in ley-arable experiments. J. Agric. Sci. (Cambridge) 60, 238–299.

McGregor, K.C., Cullum, R.F., Mutchler, C.K., 1999. Long-term management effects on runoff, erosion, and crop production. Trans. ASAE 42, 99–105.

Meyer, L.D., Wischmeier, W.H., Foster, G.R., 1970. Mulch rates required for erosion control on steep slopes. Soil Sci. Soc. Am. J. 34, 928–931.

Miglierina, A.M., Iglesias, J.O., Landricini, M.R., Galantini, J.A., Rosell, R.A., 2000. The effects of crop rotation and fertilization on wheat productivity in the Pampean semiarid region of Argentina. 1. Soil physical and chemical properties. Soil Till. Res. 53, 129–135.

Morón, A., 2003. Efecto de las rotaciones Cultivos-Pasturas sobre la fertilidad de los suelos en ensayos de larga duración del INIA La Estanzuela (1963–2003). Investigaciones Agronómicas 20, 1–6., http://www.ppi-ppic.org/ppiweb/iaarg.nsf/$homepage/$first.

Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon, and organic matter. In: Page, A.L., Miller, D.R. (Eds.), Methods of Soil Analysis II. Chemical and Micro-biological Properties. American Society of Agronomy, Madison, WI, pp. 539–579.

Oades, J.M., 1984. Soil organic matter and structural stability: mechanism and implications for management. Plant Soil 76, 319–337.

Paustian, K., Collins, H.P., Paul, E.A., 1997. Management controls on soil carbon. In: Paul, E.A., Paustian, K., Elliot, E.T., Cole, V.V. (Eds.), Soil Organic Matter in Temperate Agroecosystems: Long-term Experiments in North America. CRC Press, Boca Raton, FL, pp. 15–49.

Rasmussen, P.E., Collins, H.P., 1991. Long-term impact of tillage, fertilizer and crop residue on soil organic matter in temperate semi-arid regions. Adv. Agron. 45, 93–134.

Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241, 155–176.

Steinbach, H.S., Alvarez, R., 2006. Changes in soil organic carbon contents and nitrous oxide emissions after introduction of no-till in Pampean agroecosystems. J. Environ. Qual. 35, 3–13.

Tisdall, J.M., Oades, J.M., 1982. Organic matter and water-stable-aggregates in soil. J. Soil Sci. 33, 141–163.

Trujillo, W., Fisher, M.J., Lal, R., 2006. Root dynamics of native savanna and introduced pastures in the Eastern Plains of Colombia. Soil Till. Res. 87, 28–38.

Vu, V.T.K., Prapaspongsa, P., Poulsen, H.D., Jørgensen, H., 2008. Prediction of manure nitrogen and carbon output from grower-finisher pigs. Anim. Feed Sci. Technol. 151, 97–110.

West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation. Soil Sci. Soc. Am. J. 66, 1930–1946.

Yoder, R.E., 1936. A direct method of aggregate analysis of soil and study of the physical nature of erosion losses. J. Am. Soc. 28, 337–351.

Zheng, F.L., Merrill, S.D., Huang, C.H., Tanaka, D.L., Darboux, F., Liebig, M.A., Halvorson, A.D., 2004. Runoff, soil erosion, and erodibility of conservation reserve program land under crop and hay production. Soil Sci. Soc. Am. J. 68, 1332–1341.