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Soil quality and productivity under zero tillage and grazing on Mollisols in Argentina – A long-term study

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ABSTRACT

The growing global demand for food, fibers and energy has triggered a scientific and political debate on how to attain increasing land productivity without further degrading soils. The objective of this study was to quantify the effect of long-term no-till cultivation with light grazing on soil quality, land productivity, and resource use efficiency. The experiment was established in 1993 with two main treatments, no-till (NT) and conventional tillage (CT), sub-divided into grazed and ungrazed subplots, in a paired strip design with three repetitions. Crops included sunflower, corn, soy and wheat, and stubbles were grazed for at 3 months with young animals. Soil samples were collected in 2015 and determinations included total carbon and its fractions, total nitrogen, microbial biomass carbon, soil moisture contents, aggregate size class distribution, volumetric aggregate weight, mean weight diameter change, maximum bulk density, total infiltration, and saturated hydraulic conductivity. Crop production was on average 13% higher in NT than in CT, and grazing had no effect on yields. NT increased organic matter contents by 6% and CT diminished it by 1.7% in the top 0.10 m compared to the original value in 1993, and showed no significant variation at 0.10–0.20 m depth. The labile C fractions and microbial biomass carbon showed a similar trend with highest values in the non-grazed NT topsoil. We found positive relationships between microbial biomass and labile carbon and nitrogen fractions only for the NT soils. All soil physical quality indicators had better values for NT compared to CT soils, and grazing had no effect. The results of this long-term experiment gave evidence that a NT system with light grazing was a feasible land management that increased land productivity in a semiarid environment.

1. Introduction

The growing global demand for food, fibers and energy has triggered a scientific and political debate on how to reach the goals of increasing land productivity without further degrading soils and thus undermining the delivery of vital ecosystem services (IFAD and UNEP, 2013; Victoria et al., 2012). Some authors stipulate that agricultural production should move towards *ecological intensification* (Cassman, 1999; Doré et al., 2011; Tilman et al., 2002), without, however, specifying the new technologies involved in this process. On the other hand an advance of agricultural frontiers into marginal, dry lands, where land use change will bring about drastic degradation of land and water resources (Nosetto et al., 2011, 2005; Zach et al., 2006). In these areas the predominant use of land is mixed systems that include animal husbandry as well as grain production. In many semi-arid regions, zero tillage facilitated agricultural land use and continued cultivation. Thus, in these systems, foraging animals coexist with agricultural production, often in crop stubs. However, it has been shown that grazing animals have a negative effect on organic matter, on soil structure and increase the soil's bulk density (Silva and Imhoff, 2003). Results of Quiroga et al. (2009) indicated that the introduction of grazing animals in no-till crop systems would not be detrimental to soil conditions and quality in semiarid region, but grazing animals in CT damaging the carbon content and the soil structure.

Zero tillage or no-till (NT) has been used for several decades in conservation agriculture and has been shown to improve or at least maintain soil quality while providing adequate crop yields (Hollinger et al., 2005; Lal et al., 2007; López et al., 2012; Melero et al., 2009). It has also been shown to improve the water use efficiency of crops (Noellemeyer et al., 2013) and it might also favor nutrient cycling through enhanced biological activity (Frasier et al., 2016). Some authors recommend to adapt this practice for smallholder farmers in order to sustainably increase yields (Serraj et al., 2012). Numerous studies have shown that NT increases organic matter contents of the surface

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soil (Fernández et al., 2010; López et al., 2012; Puget and Lal, 2005). Nevertheless it has been questioned that carbon accrual under NT only affects the uppermost few centimeters of the soil while the total C stocks of the soil profile would be unchanged (Blanco-Canqui et al., 2011).

However, several studies showed disadvantages of no-till, such as subsoil compaction (Botta et al., 2013), delay of germination due to lower temperatures (Bolliger et al., 2006; Sarkar and Singh, 2007), nitrogen immobilization and deficiency (Alvarez and Steinbach, 2009; Sainju et al., 2006), and lower yields especially of wheat and other gramineae (Alvarez and Steinbach, 2009). These disadvantages would threaten the sustainability of crop production under NT and render it unsuitable for attaining the UN's Millennium Development Goals. Our hypothesis was that NT under a more diversified production system, including a wide range of different crops in the rotation, and using part of the crop stover for animal forage could be a solution to this dilemma.

The objective of this study was to quantify the effect of long-term no-till cultivation on soil quality, land productivity, and resource use efficiency. We also sought to evaluate the sustainability of a mixed crop-livestock NT system compared to conventional cultivation, in a semiarid environment.

2. Materials and methods

2.1. Study site

The study was carried out in the central semiarid region of Argentina. The study site is in a gently rolling landscape of deep sand deposits (at 35°42′36″S; 63°42′47″W). Soils are predominantly Entic or Typic Haplustolls according to the USDA soil taxonomy (USDA and NRCS, 2010), with a typical profile of A (0–0.18 m), AC (0.18–0.46 m), C (0.46–1.00 m) and C_k (1.00–1.86 m) horizons, and an underlying calcium carbonate hardpan.

In August 1993 the trial was started on a private farm with two main treatments, NT and CT, which are sub-divided into grazed and ungrazed subplots of 100 m length by 15 m width each, in a paired strip design with three repetitions. The resulting treatments were no-till non-grazed and grazed (NTNG and NTG), and conventional tillage non-grazed and grazed (CTNG and CTG). Plots were cultivated using standard farm equipment and common farm level technology for weed and pest control, for details please refer to Quiroga et al. (2009). The crop sequence from 1993 until 2015 included sunflower (*Helianthus annuus* L.), wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.), corn (*Zea mays* L.), 4 years of alfalfa (*Medicago sativa* L.) and tall fescue (*Festuca arundinacea* (*Schreb.*) *Darbysh. = Schedonorus arundinaceus (Schreb.) Dumort*) pasture, soybean (*Glycine* max (L.) Merr.), and winter cover crops (*Secale cereale, Vicia villosa* Roth.). The tillage treatments were NT, where all crops and the pasture were established with a direct drill after herbicide application for fallow; and CT with a disk plow and spine harrow for fallowing and before seeding. Crops were fertilized with nitrogen (N) and phosphorus (P) at rates of 10 kg ha^{-1} of P and 40–60 kg ha^{-1} of N each year. In the grazed plots, crop stubbles or winter cover crops were lightly grazed with either heifers or steers (estimated live body weight 300 kg) for fattening, with an average stocking rate of 2 animals per hectare during 3 months.

2.2. Soil sampling and analysis

Soil samples were collected in November 2015 at seven points at 4 m distance each, along a linear transect in each plot. Sampling was carried out with an auger of 0.032 m diameter at 0 to 0.10, and 0.10 to 0.20 m depth, all within the limits of the A horizon, and within the tillage depth of the disk plow. The seven subsamples thus obtained were mixed in the field, air dried and passed through a 2 mm sieve for further analyses.

Soil samples for bulk density (BD) were also collected with a steel cylinder (0.471 m^{-3}) at 0–0.10 and 0.10–0.20 m depth by triplicate in each plot. Samples were oven-dried at 105 °C and weighed for BD calculation.

For microbial biomass determinations samples were taken from the non-grazed plots only in the same way as described above at 0–0.05 and 0.05–0.1 m depth. Samples were stored at field moisture in a refrigerator at 2 °C (for less than two months) to prevent mineralization (Wu and Brookes, 2005). Soils were extracted using the fumigation-extraction method (Voroney, 2006) with a ratio soil to extractant (K_2SO_4, 0.5 M) of 1:2. Microbial biomass carbon (MBC) was determined according to Vance et al. (1987). MBC was calculated according to the following equation $MBC = E_C/0.45$, where E_C is the difference between organic C extracted from the K_2SO_4 extracts of fumigated and non-fumigated soils, both expressed as μg C g^{-1} oven dry soil (Wu et al., 1990). The metabolic quotient was calculated as the ratio between soil total respiration and microbial biomass carbon. Respiration data from non-disturbed soil samples from 0.05 m depth were used as reported by Fernández et al. (2010). Samples of undisturbed soil from 0 to 0.06 m depth were incubated in closed vessels in a growth chamber at 24 °C and at 80% of their water holding capacity. The respired CO_2 was trapped in 0.5 N NaOH and the excess was titrated with 0.5 NHCl. Respiration was determined at 14 days.

Total carbon (C) and nitrogen (N) analyses were carried out using dry combustion with a CN auto analyzer (LECO – TrueSpec®). Available phosphorus (P) was determined by the Bray- Kurtz extraction with ammonium fluoride in hydrochloric acid. Soil fraction separation was based on complete soil dispersion followed by wet sieving (Noellemeyer et al., 2006 adapted from Cambardella and Elliott, 1994). The soil suspension obtained was wet sieved through 53-μm and 100-μm sieves for 3 min (Fritsch Analysette Spartan Vibratory 3). Soil fractions collected were placed in metal jars in oven at 60 °C until complete drying. Dry weight of the fractions > 100 μm (particulate organic C and N; Cp and Np) and 100–53 μm (intermediate organic C and N; Ci and Ni) were recorded, and the weight difference with the original sample (50 g) was used to calculate weight of fraction < 53 μm (mineral associated C and N; Cm and Nm). Carbon and N analysis were performed by dry combustion with a CN auto analyzer (LECO – TrueSpec®).

At planting and harvest of all crops until 2015, soil moisture was determined on samples taken in 0.20 m intervals down to a total depth of 1.40 m. On the same samples, water contents at 30 and 1500 kPa (field capacity and permanent wilting point) were determined with the Richards membrane equipment, and the available water (AW) contents were calculated as moisture contents minus permanent wilting point moisture. Fallow efficiency (FE) was calculated as the percentage of rainfall contained in the soil at the end of fallow using the following equation (Mathews and Army, 1960):

$$FE\ (\%) = \frac{AWf - AWi}{\text{rainfall during fallow}} \times 100 \tag{1}$$

Water use efficiency (WUE), i.e. grain production per unit of water used, was calculated from rainfall data and the change in soil water storage during growing periods of crops according to the following equation (Moret et al., 2006):

$$WUE\ (\text{kg ha} - 1\ \text{mm} - 1) = \frac{Y}{CWU} \tag{2}$$

where Y is mean grain yield of each crop (kg ha^{-1}); CWU (mm) is the crops' apparent mean consumptive water use, which was calculated according to the following formula:

$$CWU = AWi - AWf + R \tag{3}$$

where AW*i* is the initial available water content of the soil at seeding (mm); AW*f* is the final water content of the soil at harvest (mm) and R is rainfall during the growing season (mm); all water contents measured to 1.40 m depth. This definition includes water consumption by crop transpiration, as well as runoff, deep drainage, and soil evaporation. All values used for calculations were the means of the three subsamples per

Table 1
Yields (Mg ha^{-1}) of last six cropping seasons for crops in no-till non-grazed (NTNG), no-till grazed (NTG), and conventional tillage non-grazed (CTNG), and grazed (CTG) plots. Different letters in a same column indicate significant differences among treatments (Tukey test; $p < 0.10$).

Season (years) Crops	NTNG		NTG		CTNG		CTG		Rainfall during the crop season (mm)
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	
2010–11									
Soybean	2.98a	113.7	2.27ab	70.4	2.49ab	166.7	1.79b	159.6	476
2011–12									
Sunflower	3.45	223.9	3.35	74.4	3.88	126.4	3.36	249.5	651
Soybean	3.66	49.2	4.08	389.5	3.62	136.8	3.20	204.4	600
Corn	7.31a	11.4	7.27a	42.6	6.22ab	24.8	6.08b	51.17	600
2012–13									
Soybean	3.68	84.0	3.69	149.5	3.60	168.4	3.60	101.1	300
Corn	8.80a	654.1	6.06b	376.9	8.45a	321.1	5.98b	231.3	315
2013–14									
Soybean	3.17a	96.6	2.42b	155.2	2.72ab	100.7	2.38b	180.0	525
Corn	10.9	360.5	11.6	756.3	9.11	1499	10.5	900.3	525
2014–15									
Sunflower[a]	2.57		2.51		2.29		2.10		409
2015–16									
Soybean	5.18ab	323.4	5.58a	329.0	4.49b	190.3	4.57b	240.9	568

[a] No data for the repetitions, average yield was reported.

Table 2
Organic matter (OM), total nitrogen (N) contents, and pH of soil under no-till non-grazed (NTNG), no-till grazed (NTG), conventional tillage non-grazed (CTNG), and grazed (CTG) treatments sampled in November 2015. Different letters in the same column indicate significant differences (Tukey, $p < 0.05$).

	OM (g kg^{-1})				Total N (g kg^{-1})				pH			
Depth (m)	0–0.10		0.10–0.20		0–0.10		0.10–0.20		0–0.10		0.10–0.20	
Initial 1993	20.9		17.3		1.05		0.80		–		–	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
NTNG	26.1 a	0.14	16.1	0.21	1.30 a	0.01	0.90	0.01	6.7 a	0.09	6.5 a	0.03
NTG	17.9 b	0.04	14.1	0.12	1.20 a	0.002	0.70	0.01	6.7 a	0.02	6.4 ab	0.17
CTNG	19.2 b	0.18	16.8	0.16	1.00 b	0.01	0.80	0.01	6.2 b	0.06	6.2 b	0.05
CTG	16.4 b	0.28	15.9	0.15	1.00 b	0.01	0.80	0.01	6.6 ab	0.04	6.3 b	0.01

treatment (crop, tillage, and year).

A third set of soil samples (0–0.10 and 0.10–0.20 m) was collected in the same manner for aggregate size distribution determination. Air-dried samples were manually disaggregated with very gentle pressure through rupture across the natural planes of weakness, then the samples were shaken through a battery of sieves with diameters of 8, 4, 3, 2 mm during 30 min. Manual disaggregation and sieving followed the technique described by Larney (2006). The weight of each aggregate fraction was determined and expressed as the percentage of total soil mass, and the mass of aggregate fractions retained by 4 to 2 mm sieves were pooled for statistical analysis.

The volumetric weight of aggregate fractions (VAW) was determined by accurately weighing the aggregates contained in a 1 L volume (Fernandez et al., 2016). Mean weight diameter change after wet sieving of aggregate fractions according to De Boodt et al. (1967) was recorded and the structural stability indexed (SSI) was calculated as $SSI = \frac{1}{\text{change in mean weight diameter}}$ thus higher values reflected better structural stability. Data from both soil depths were averaged to give a 0–0.20 m depth values. Larger bulk soil samples (0–0.20 m) were taken for the determination of maximum bulk density and susceptibility to compaction with the Proctor test (AASHO Standard T-99).

Infiltration assays were carried out with double ring infiltrometers (Reynolds, 2006) with six replicates per plot in the field. Saturated hydraulic conductivity was determined on intact soil cores (0–0.10 m and 0.10–0.20 m depth) in the laboratory following the technique described by Cook (2006) with three replicates per plot.

2.3. Crop yield and residue cover determinations

Crop production was determined by manual harvest of three subsamples of each treatment (NTNG, NTG, CTNG, and CTG) that represented an area of 1 m^2 in the case of wheat and 2 m^2 for corn, sunflower and soybean. The percentage of soil cover with plant residues was measured using a line-transect method (López et al., 2003), by stretching a 5-m measuring tape across crop rows and counting the number of times a 0.10-m mark coincided with a residue. The percentage residue cover was obtained by multiplying this number by 2. This measurement was carried out in four replicates per treatment.

2.4. Statistical analysis

Mean values of the three replicates of all crop and soil variables were compared among the four treatments (NTNG, NTG, CTNG, CTG) using one-way analysis of variance, partitioned according to soil depth, and separated by the Tukey test at the 90 and 95% confidence level, using InfoStat/P software (Di Rienzo et al., 2009). Regression analysis was also carried out with the same software for MBC and carbon data.

3. Results and discussion

3.1. Soil moisture and crop yields

Water storage during fallow was crucial for crop production, and improving fallow efficiency becomes a decisive factor for increased crop productivity. Fallow efficiency is usually very low, ranging between 0 and 25% of rainfall during fallow being stored in the soil (Fernandez et al., 2008; Lampurlanes et al., 2002; Moret et al., 2006). Fallow efficiency was different among winter and summer, and between tillage systems, ranging from − 40 to 68% in CT and 1.3 to 76% in NT (data not shown). Winter fallows were more effective than

Table 3
Carbon and nitrogen fractions in no-till non-grazed (NTNG), no-till grazed (NTG), conventional tillage non-grazed (CTNG) and grazed (CTG) soils at two depths. Mineral associated carbon (Cm), nitrogen (Nm), intermediate carbon (Ci), nitrogen (Ni), particulate carbon (Cp), and nitrogen (Np). Different letters in the same row indicate significant differences (Tukey, $p < 0.05$).

	Depth (m)	NTNG		NTG		CTNG		CTG	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE
Cm	0–0.10	9.2b	0.04	10.7a	0.03	9.0b	0.0033	8.5b	0.05
g kg^{-1}	0.10–0.20	10.6	0.09	8.7	0.08	9.3	0.06	8.9	0.04
Ci	0–0.10	2.1a	0.01	1.6b	0.01	1.5b	0.01	1.4b	0.0033
g kg^{-1}	0.10–0.20	1.3a	0.01	1.2ab	0.0003	1.1b	0.0002	1.2ab	0.0003
Cp	0–0.10	3.8a	0.05	2.7ab	0.03	2.3b	0.003	1.7b	0.02
g kg^{-1}	0.10–0.20	1.4	0.01	1.2	0.0001	1.4	0.01	1.0	0.02
Nm	0–0.10	0.8	0.0003	1.0	0.003	0.8	0.0033	0.7	0.0033
g kg^{-1}	0.10–0.20	1.1	0.01	0.9	0.01	0.8	0.0003	0.9	0.0003
Ni	0–0.10	0.2	0.0001	0.2	0.001	0.2	0.0004	0.2	0.0033
g kg^{-1}	0.10–0.20	0.1	0.0003	0.1	0.0003	0.1	0.01	0.1	0.0003
Np	0–0.10	0.3a	0.0003	0.3ab	0.003	0.2bc	0.0001	0.1c	0.0033
g kg^{-1}	0.10–0.20	0.1	0.0006	0.1	0.0001	0.1	0.003	0.1	0.0001

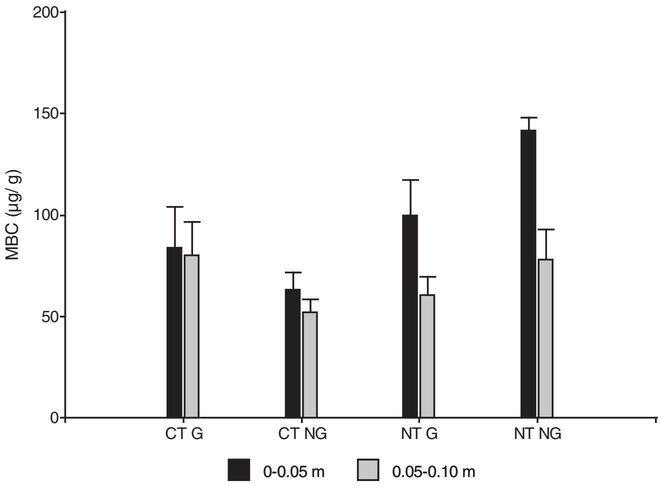

Fig. 1. Microbial biomass carbon (MBC) contents in soils under No-till without grazing (NTNG), no-till with grazing (NTG), conventional tillage without grazing (CTNG), and conventional tillage with grazing (CTG) at different depth intervals. Bars indicate standard error.

summer fallows in both CT (24%) and NT (46%), and on average NT (32%) was more efficient than CT (21%). Lampurlanes et al. (2002) already indicated that NT was more effective for fallow water storage, specifically when crop residues were left on the soil surface and not buried by plowing. Likewise, Fernandez et al. (2008) highlighted the importance of residue cover for efficient water storage in the soil. NT had higher proportions of residue cover than CT (data not shown), which were generally well above the threshold level for water retention (60%) (Quiroga et al., 2015), while CT had values that were on average below the critical level for wind erosion prevention (30%) (Mendez and Buschiazzo, 2010).

NT had more moisture at planting with an average of 110 mm for CT and 146 mm for NT (data not shown). These improved conditions resulted in higher crop yields under NT compared to CT, and the differences were 0.29, 1.11, 0.28, and 0.65 Mg ha^{-1} more for sunflower, corn, soybean and wheat respectively (Table 1). On average NT-crops produced 13% more than those managed under CT, resulting in enhanced land productivity for NT systems. The beneficial effect of NT on the soils' moisture conditions and fallow efficiency is especially important for semiarid regions where rainfall does not cover the crop's requirements. For the semiarid North American Great Plains, Baumhardt and Jones (2002) also found higher water storage after fallow in NT plots, although the wheat or sorghum yields were not consistently higher. López and Arrúe (1997) and Hernanz et al. (2014) even found lower barley yields under NT in different semiarid regions of Spain. However, many studies coincide in positive effects of NT on the water balance of semiarid agroecosystems and subsequently improved crop yields (Alletto et al., 2011; Barzegar et al., 2003; Farooq et al., 2011; Lampurlanes et al., 2002; Rockström et al., 2009).

The light grazing of crop stubble did not affect crop yield significantly neither in NT nor in CT, similar to results obtained by Franzluebbers and Stuedemann (2008) and Siri-Prieto et al. (2007) for NT systems with grazed winter cover crops in the southern United States. Bell et al. (2011) analyzed the existing literature and found that although it is supposed that in integrated crop-livestock systems grazing-induced soil damage would affect subsequent crop production, there is very little evidence of reduced yields when grazing intensity was light. Therefore, and under these conditions, the added benefits of intensified land use by cattle grazing in the integrated crop-livestock systems would result in higher net returns from land and less vulnerable diversified production systems (Lemaire et al., 2015; Pacín and Oesterheld, 2013).

3.2. Soil fertility indicators

The original values of soil organic matter (OM) contents in this field were 20.9 and 17.3 g kg^{-1} for 0.0–0.10 and 0.10–0.020 m depth respectively (Table 2). After 22 years of NT without grazing, the organic matter increased to 26.1 g kg^{-1} in the surface layer and showed only a slight variation in the deeper interval of the Ap horizon. All other treatments had values ranging from 16.4 to 17.9 g kg^{-1} which were not different among each other in the upper layer and no differences were found in the deeper layer, similar to results reported from NT-CT comparison in central Italy (Mazzoncini et al., 2016). In field studies in semiarid Spain comparable results were reported by López et al. (2012) who found that NT soils on average had 20% more carbon in the surface horizon than CT soils. Grazed treatments tended to have slightly lower OM contents with statistical significance only for the NT plots and in the surface layer. Grazing reduced OM contents, compared to non-grazed treatments, but the effect was relatively smaller in CT than in NT (-3 versus -8 g kg^{-1}, respectively). This small difference may have accounted for the above mentioned lack of response in crop yields to grazing.

For total nitrogen (N), tillage treatments differed only in the surface soil layer, with higher concentration for NT soils and no differences among grazed and non-grazed plots. CT plots showed similar N contents as the initial soil whereas NT plots had higher total N. These results are coherent with the higher OM contents in NT soils and similar trends have been reported previously (Alburquerque et al., 2015). A preliminary study on the response of corn to N fertilization in the same

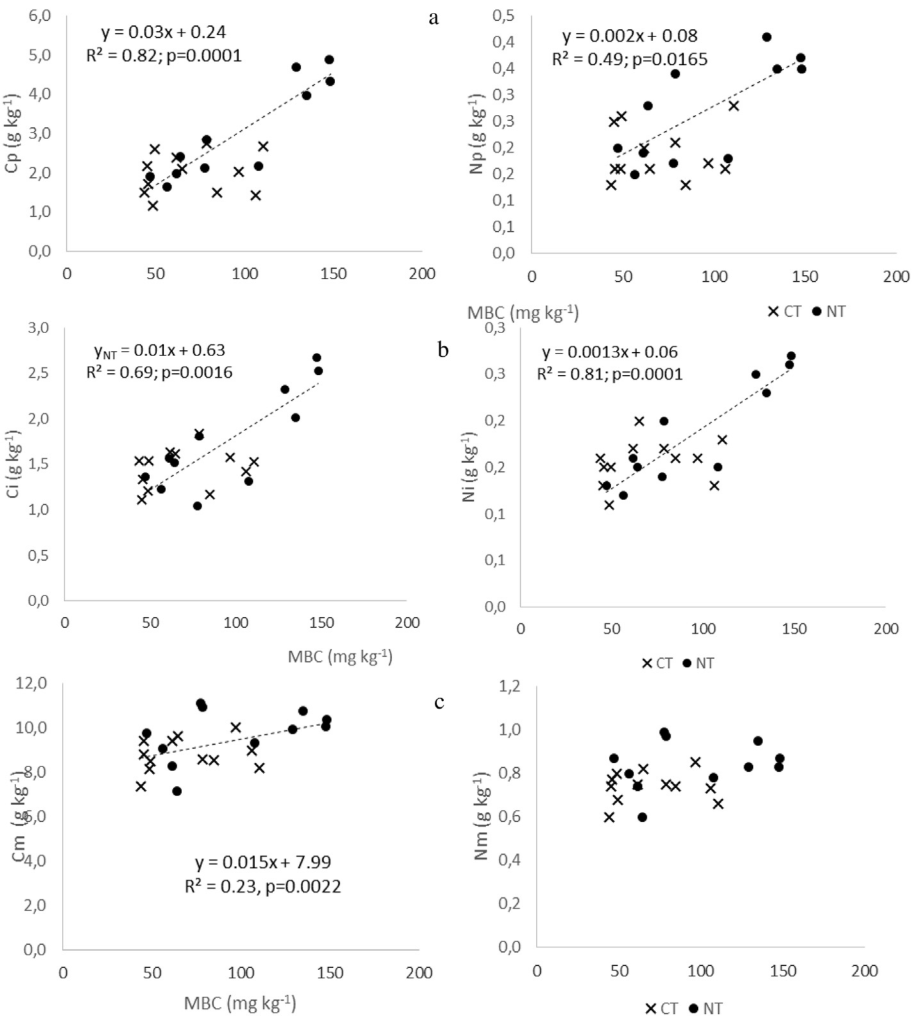

Fig. 2. Relationships between microbial biomass carbon (MBC) and a) particulate carbon and nitrogen (Cp; Np), b) intermediate carbon and nitrogen (Ci; Ni), and c) mineral associated carbon and nitrogen (Cm; Nm) in no-till (NT) and conventional tillage (CT) of soil samples taken at 0.05 m for MBC and 0–0.10 m for carbon and nitrogen fractions.

Table 4
Respiration, microbial biomass carbon (MBC) and metabolic quotient (qCO_2) for no-till (NT) and conventional tillage (CT) soils without grazing at 0.05 m depth. Respiration data were taken from Fernández et al. (2010) corresponding to non-disturbed samples from 0.06 m depth.

Respiration (mg kg^{-1})		MBC (mg kg^{-1})		qCO_2	
NT	CT	NT	CT	NT	CT
131	104	142	63	0.92	1.7

Table 5
Aggregate size class distribution, soil stability index (SSI), maximum bulk density (max BD), and relative compaction (BD/maxBD*100) in soils under no-till without grazing (NTNG), no-till with grazing (NTG), conventional tillage without grazing (CTNG), and conventional tillage with grazing (CTG) at 0–0.20 m depth. Different letters in the same column indicate significant differences (Tukey $p < 0.05$).

	SSI		Max. BD Mg m^{-3}		Relative compaction
	Mean	SE	Mean	SE	
NTNG	0.86 a	0.19	1.39 b	0.02	80 b
NTG	0.74 a	0.08	1.35 b	0.02	82 ab
CTNG	0.56 b	0.08	1.45 a	0.03	80 b
CTG	0.41 c	0.03	1.45 a	0.01	84 a

experiment showed that NT plots did not respond to low rates whereas CT crops showed a linear response to increasing N rates (Civalero et al., 2014), indicating that N mineralization in NT was higher than in CT, covering crop requirements to a greater degree.

3.3. Soil carbon and nitrogen fractions and microbial biomass carbon

All carbon fractions showed significant differences between treatments in the 0–0.10 m depth layer, and intermediate and particulate carbon were also different in the deeper layer (Table 3). The N contents of these fractions were generally not different among tillage treatments except for the particulate N in the 0–0.10 m layer. Both particulate and intermediate carbon fractions were highest in the NTNG soils with no differences among the other treatments. The mineral associated carbon fraction, however, was highest in the grazed NT soil. Grazing diminished the carbon contents of the labile fractions as would be expected from the lower returns of organic residues to the soil. Cultivation in the long-term leads to a relative enrichment of the mineral associated carbon due to the diminished amounts of labile C fractions (Zhang et al., 2007). Accordingly, the proportion of particulate carbon (Cp) in total carbon (i.e. Σ Cp + Ci + Cm) was highest in NTNG and lowest in CTG. The enhanced proportion of labile organic material in NT also had a positive impact on the soil's microbiota and was reflected by higher microbial biomass carbon (MBC) contents especially in the NTNG soil in the surface 0.05 m, while at greater depth no differences were found (Fig. 1). It is common that MBC shows greater values only at the very surface of the soil when comparing tillage systems (Sun et al., 2011; Zuber and Villamil, 2016) which might reflect the response of the

Table 6
Aggregate size distribution (%) for no-till non-grazed (NTNG), no-till grazed (NTG), conventional tillage non-grazed (CTNG) and grazed (CTG) at two soil depths. Different letters in the same column indicate significant differences (*p* values shown for each case).

Depth	0–0.10 m						0.10–0.20 m					
Aggregate size (mm)	> 8		2 a 8		< 2		> 8		2 a 8		< 2	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
NTNG	61.9 a	2.3	23.8 ab	0.7	14.1 c	1.2	60.8 ab	2.1	22.8 b	0.9	16.3 b	1.2
NTG	65.0 a	1.7	26.0 ab	0.7	14.3 b	0.9	67.0 a	0.9	18.9 b	0.3	14.2 b	0.9
CTNG	42.0 c	2.6	27.0 a	0.7	31.3 a	2.5	47.6 c	3.8	27.2 a	1.9	25.1 a	2.5
CTG	53.0 b	1.9	20.9 b	0.7	23.7 a	2.9	52.3 bc	4.3	23.7 ab	1.6	23.9 a	2.9
p	0.0001		0.02		0.0001		0.0036		0.006		0.005	

Table 7
Volumetric weight (g cm^{-3}) of aggregates (VAW) of different diameters. Different letters in the same column indicate significant differences ($p < 0.10$) between treatments. NTNG = no-till non-grazed, NTG = no-till grazed, CTNG = conventional tillage non-grazed, CTG = conventional tillage grazed.

Diameter (mm)	≤ 2		2–3		3–4		4–8		≥ 8	
0–0.10 m										
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
NTNG	1.11	0.1	0.78	0.03	0.76 b	0.02	0.74 b	0.02	0.86 b	0.03
NTG	1.16	0.07	0.78	0.02	0.77 b	0.01	0.78 ab	0.02	0.87 ab	0.02
CTNG	1.10	0.02	0.82	0.01	0.85 a	0.01	0.81 ab	0.03	0.91 ab	0.03
CTG	1.16	0.01	0.81	0.02	0.84 a	0.02	0.85 a	0.02	0.97 a	0.02
0.10–0.20 m										
NTNG	1.09	0.02	0.74 b	0.01	0.77 b	0.02	0.80	0.02	0.89	0.02
NTG	1.09	0.02	0.80 ab	0.01	0.78 ab	0.01	0.81	0.01	0.93	0.01
CTNG	1.12	0.01	0.77 b	0.02	0.81 a	0.01	0.82	0.03	0.95	0.02
CTG	1.15	0.02	0.80 a	0.02	0.84 a	0.03	0.86	0.01	0.95	0.01

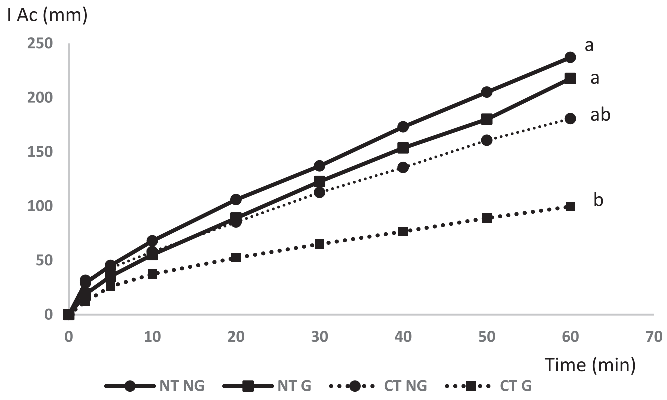

Fig. 3. Accumulated infiltration (I Ac, mm) in soils under no-till without grazing (NTNG), no-till with grazing (NTG), conventional tillage without grazing (CTNG), and conventional tillage with grazing (CTG) at different depth intervals. Different letters indicate significant differences in total infiltration after 1 h (Tukey p: 0.044, CV: 28%).

microbial populations to carbon input through residues at the soil's surface (Börjesson et al., 2016). Kallenbach et al. (2015) postulated that greater populations of the soil's microbial organisms transform and stabilize more carbon, thus enhancing carbon sequestration. Our data showed that the relationships between MBC and soil carbon fractions were only significant for NT soils and not for CT (Fig. 2). Both labile (particulate and intermediate) carbon and nitrogen fractions showed strong correlations with MBC (Fig. 2a and b). This indicated that in the NT soils there is a mutual dependence of labile carbon and nitrogen availability and microbial activity that mediates the cycling and sequestration of these elements (Frasier et al., 2016). The fact that the mineral associated carbon fraction showed a significant, although low, correlation with MBC reinforces the idea that the microbial population is crucial for carbon sequestration in no-till systems (Mangalassery et al., 2015). Conventional tillage on the contrary, disrupted this vital cycle between residue input, labile carbon sources and microbial transformation into more stabilized carbon forms in the soil. But even NT systems with reduced residue input would suffer diminished capacity to cycle and sequester carbon (Chowdhury et al., 2015).

The efficiency of carbon utilization as expressed by the metabolic quotient was much higher in the NT soils than in CT (Table 4). While NT soils had a qCO_2 of below 1 (0.92), it was almost twice as high (1.7) in CT, indicating much higher carbon losses through respiration. The key drivers for carbon and nutrient cycling in arable soils are microbial biomass and basal respiration as measures of quantity and activity of biological functions (Creamer et al., 2015; Pulleman et al., 2012; Williams and Hedlund, 2014).

3.4. Soil structure and hydraulic properties

All indicators for soil structure (Table 5) coincided in better values for NT soils compared to CT. The structural stability index was not different between grazed and non-grazed NT, while for CT the grazed plots showed lower structural stability. Similarly, maximum bulk density was significantly lower in NT than in CT, regardless of grazing. The relative degree of compaction was highest in CTG (84%), but below the threshold value of 87 to 88% which is considered to be harmful for root development and crop yield (Håkansson and Lipiec, 2000; Naderi-Boldaji and Keller, 2016). These results indicate that the improved organic matter contents and biological activity of NT soils translated into better soil structure, higher porosity and lower susceptibility to compaction. Grazing in NT had no effect on these indicators, similar to the results reported by studies from very different geographical locations and soil types (Fernández et al., 2015; Franzluebbers and Stuedemann, 2008; Garciaprechac, 2004; Hatfield et al., 2007). The better soil structure under NT was mainly due to a stronger degree of aggregation, resulting in lesser proportion of small aggregates and more large aggregates (Table 6), following the hierarchical mechanisms of aggregate formation proposed by Tisdall and Oades (1982). The intermediate sized aggregates showed very little response to tillage and grazing treatments at both depth intervals, whereas < 2 mm aggregates

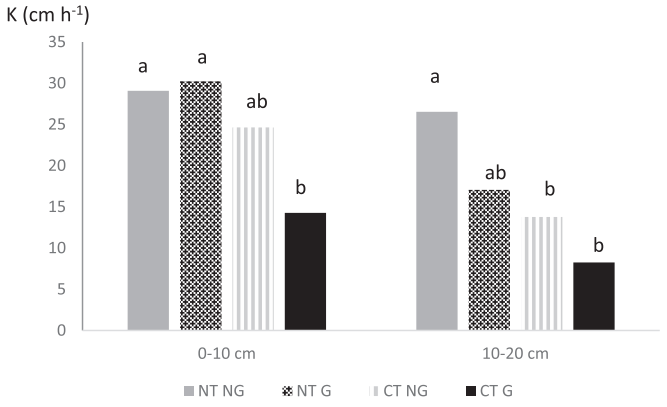

Fig. 4. Hydraulic conductivity in the two surface depth layers of soil from no-till non-grazed (NTNG), no-till grazed (NTG), and conventional tillage non-grazed (CTNG) and grazed (CTG). Different letters indicate significant differences (Tukey $p < 0.05$).

were about 100% more in CT soils compared to NT, while the latter had 25% more > 8 mm aggregates. The higher proportion of larger aggregates is especially important in semiarid environments where arable soil is exposed to wind erosion losses and a higher proportion of large aggregates in the surface soil prevents these losses to a great degree (Mendez and Buschiazzo, 2010).

The volumetric weight of aggregates (VAW) of the smallest size class of aggregates (< 2 mm) was not different among treatments at both depth intervals, and the 2–3 mm class showed significant differences only at 0.10–0.20 m depth and between grazed and non-grazed treatments (Table 7). At the same depth, the 3–4 mm aggregates behaved similarly, which could be interpreted as the compaction of subsoil as the result of cattle trampling (Hamza and Anderson, 2005). The effect of trampling at the surface might have been mitigated due to higher OM contents and therefore higher resilience to compaction (Corstanje et al., 2015). At the surface, NT had consistently lower VAW than CT in aggregates > 3 mm, and grazing had no effect on this indicator.

Higher aggregate porosity, structural stability and lower bulk density also resulted in improved infiltration (Fig. 3). Both NT soils had higher total infiltration than the CTG soils, while CTNG was not different. Although tillage is used to create macroporosity and thus enhance infiltration, this effect is short-term and the improved aggregation of the NT system produced better macroporosity than CT. Infiltration was related to the hydraulic conductivity (K) of the soil at different depths (Fig. 4). While at the surface NTNG and NTG had the same K, at 0.10–0.20 depth NTG had a considerably lower value, perhaps reflecting the higher density of intermediate size aggregates (Table 7). In the NTNG treatment, K was similar between the two depths, while in all other treatments there was a sharp decrease in hydraulic conductivity between 0 and 0.10 and 0.10–0.20 m depth, suggesting a discontinuity of the porous system. Improved infiltration and saturated hydraulic conductivity have been reported for NT systems with high residue returns or mulching (Kahlon et al., 2013), stressing the importance of OM accumulation for improved soil structure and hydraulic properties (Bronick and Lal, 2005). Low hydraulic conductivity has been associated with low yields even in a humid region (Keller et al., 2012), and as the results of this study showed, strongly influenced water availability, fallow efficiency, yield and water use efficiency of crops.

4. Conclusions

The results of this long-term experiment gave evidence to support our hypothesis that a NT system with light grazing was a feasible land management that fulfilled many of the requirements for sustainable development. Most of the analyzed parameters that responded to ecosystem functioning and the delivery of ecosystem services, such as nutrient cycling and provision, water storage and infiltration, carbon sequestration, erosion prevention, conservation of habitat for microbial populations, and food production were superior in the NT system compared to conventional tillage. We are aware, however, that NT by itself will not fulfill these goals, but only a careful planning of crop rotations and residue inputs will assure that the soil's ecosystem functions will be maintained under this system.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geodrs.2017.09.002.

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