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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