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Soil aggregation and organic carbon protection in a no-tillage chronosequence under Mediterranean conditions

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ABSTRACT

Low-intensity soil management systems like no-tillage (NT) are being increasingly accepted as an essential part of sustainable farming systems. The objective of this work was to study the effects of NT maintenance over time on soil aggregation and soil organic carbon (SOC) protection on a semiarid Mediterranean agroecosystem. A NT chronosequence was established with five phases: (i) conventional tillage (CT); (ii) NT for 1 year (NT-1); (iii) NT for 4 years (NT-4); (iv) NT for 11 years (NT-11) and (v) NT for 20 years (NT-20). N fertilization was based on pig slurry for the whole experimental area. Soil samples were collected from four depths (i.e., 0–5, 5–10, 10–20, 20–30 cm). Dry and water-stable aggregates, SOC concentration and C concentration of water-stable aggregates were measured. SOC concentration reached its maximum value after 11 years under NT. However, the differences between NT phases were only found in the 0–5 cm soil depth. In soil surface (i.e., 0–5 cm), water-stable large macroaggregates (2–8 mm) were 0.02, 0.12, 0.32 and 0.31 g g^{-1} dry soil for the NT-1, NT-4, NT-11 and NT-20 phases, respectively. C concentration of microaggregates increased in relation with the number of years under NT. SOC and water-stable macroaggregate stratification were greatest with the increase in the years under NT, emphasizing the close relationship between SOC and aggregation. In Mediterranean semiarid agroecosystems, the increase in the proportion of stable macroaggregates and the enrichment of C concentration within microaggregates are two main mechanisms of SOC protection when NT is maintained over time.

1. Introduction

Soil aggregates are the arrangement of soil particles of different sizes joined by organic and inorganic materials (Amezketa, 1999) and their stability can be used as an index of soil structure (Bronick and Lal, 2005). Soil aggregates physically protect SOC from its degradation by soil microorganisms (Beare et al., 1994a; Tisdall and Oades, 1982) and it is evidenced by the flush of carbon dioxide observed upon soil aggregates disruption (Beare et al., 1994a).

Soil structure and SOC are extremely sensitive to crop and soil management (Blanco-Canqui and Lal, 2004). It is well established that NT adoption in a previously conventionally-tilled soil results in the physical stabilization of SOC within soil aggregates (e.g., Alvaro-Fuentes et al., 2009; Six et al., 1999). During the process of SOC stabilization within soil aggregates, plant roots and fungal-derived hyphae play an important role as initial binding agents (Jastrow, 1996). According to the conceptual scheme proposed by Six et al. (2000), macroaggregate turnover is greatly reduced under NT promoting the formation of C-enriched microaggregates within macroaggregates. Moreover, the SOC sequestered within these microaggregates remains protected from microbial attack resulting in longer residence time (Blanco-Canqui and Lal, 2004). Compared to macroaggregates, the biochemical structure of the SOC that stabilizes microaggregates tends to be highly processed and recalcitrant (Elliott, 1986). Also, soil biological activity under NT is increased (Madejon et al., 2009) promoting the production of organic binding by-products that stabilize soil aggregates.

When NT is maintained over time, soil aggregate stability is enhanced (Beare et al., 1994b) leading to the increase of total SOC (West and Post, 2002). In Florida, Ochoa et al. (2009) studied a NT chronosequence of 0, 6, 10 and 15 years under NT in commercial plots. They observed a relationship between the increase in surface soil water-stable macroaggregates and the hydrolysable organic carbon with longer years under NT. Thus, they concluded that continuous NT is beneficial for SOC buildup in soil macroaggregates.

In the Mediterranean semiarid agroecosystems, intensive tillage practices have led to the loss of soil structure and soil degradation (Alvaro-Fuentes et al., 2007). Recently, conservation tillage systems (e.g., reduced tillage or NT) have been increasingly adopted in these areas due to its agricultural and environmental benefits (Kassam et al., 2009). In these semiarid systems, several studies have investigated the impacts of adoption of continuous NT on soil aggregation and physical C stabilization (e.g., Alvaro-Fuentes et al., 2009; Plaza-Bonilla et al., 2010). Nevertheless, the vast majority of these studies has been based

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on time-point comparisons (Staley et al., 1988). As a result, there is a lack of information about the continuous maintenance of NT on soil aggregation and SOC protection. Consequently, the objective of this experiment was to study the temporal dynamics of soil aggregation and SOC protection after the conversion of CT to NT in a rainfed Mediterranean agroecosystem. In order to achieve this objective we established a NT chronosequence 20 years ago in representative Mediterranean dryland agroecosystems located in northeast Spain. We hypothesized that the maintenance of NT results in greater SOC protection within C-enriched water-stable macroaggregates.

2. Materials and methods

2.1. Experimental site

A NT chronosequence experiment located in the semiarid Ebro river valley, NE Spain (41°48′ N, 1°07′ E, 330 m), was established 20 years ago in a previously intensive-tilled field of 7500 m^2. Mean annual precipitation, mean air temperature and mean annual evapotranspiration in the area are 430 mm, 13.8 °C and 855 mm, respectively. The soil was classified as Typic Xerofluvent (Soil Survey Staff, 1994), with the following properties in the Ap horizon (0–28 cm) at the start of the experiment: pH (H_2O, 1:2.5): 8.5; electrical conductivity (1:5): 0.15 dS m^{-1}; $CaCO_3$ eq. (%): 40; water retention (kg kg^{-1}): 0.16 and 0.05 at −33 and −1500 kPa, respectively; sand (2000–50 μm), silt (50–2 μm) and clay (<2 μm) content: 475, 417 and 118 g kg^{-1}, respectively. The edaphoclimatic conditions of the experiment could be considered as representative of the most part of the cropping systems located in the dryland Mediterranean areas. In 1990, 1999, 2006 and 2009 successive portions of 1500 m^2 of the intensive-tilled field (i.e., 7500 m^2) were transformed to NT. Thus, in 2010, a surface of 1500 m^2 remained under CT and 6000 m^2 under NT with different years: 1 (NT-1), 4 (NT-4), 11 (NT-11) and 20 (NT-20) years. In all five chronosequence phases the cropping system consisted in winter cereal rotation. Fertilization was based on pig slurry homogeneously applied for the whole experimental area in a dose of 50 kg N ha^{-1} $year^{-1}$ depending of the slurry composition. The CT treatment consisted of one pass of a moldboard plow to 25 cm depth immediately followed by one or two passes with a cultivator to 15 cm, both in September. The NT treatments consisted of a total herbicide application (1.5 L 36% glyphosate per hectare) for controlling weeds before sowing. Planting was performed with a direct drilling disk machine set to 2–4 cm in November. Prior to the set up of the experiment, the historical management of the field was based on conventional intensive tillage with moldboard plowing and pig slurry additions, similar to the management applied to the CT phase of the chronosequence. Neither slope nor differences in soil characteristics in the whole experimental area were found. The treatments were arranged in a randomized design with replicated plots. More details about the experimental design are given in Álvaro-Fuentes et al. (in press).

2.2. Soil sampling and analyses

Soil sampling was performed in July 2010, right after crop harvest. Each phase of the chronosequence was divided in three areas. In each area, a composite sample was collected from three samples randomly selected. Soil samples were obtained using a flat spade in four soil layers from 0 to 30 cm depth (0–5, 5–10, 10–20 and 20–30 cm) and were stored in crush-resistant airtight containers. Once in the laboratory, soil was sieved with an 8 mm-sieve and air-dried at room temperature. For each sample, dry soil aggregate and water-stable aggregate distributions were obtained. Water-stable aggregate size separation was performed in a 100 g 8-mm sieved soil sub-sample according to a modified wet sieving method adapted from Elliott, (1986). The method is extensively described in a previous work (Plaza-Bonilla et al., 2010). Four water-stable aggregate fractions were obtained: (i) large macroaggregates (2–8 mm), (ii) small macroaggregates (0.250–2 mm), (iii) microaggregates (0.053–0.250 mm) and (iv) silt-plus clay-sized particles (<0.053 mm). All water-stable aggregate fractions were oven-dried at 50 °C (48 h) in aluminum trays and weighed. Sand content of the aggregate classes (>0.053 mm) was determined dispersing 5 g of a subsample in a sodium hexametaphosphate solution (5 g L^{-1}) using a reciprocal shaker. Sand correction was performed in each aggregate-size class because sand was not considered part of those aggregates (Elliott et al., 1991). The dry aggregate size distribution was conducted placing 100 g of air-dried sub-sample (8 mm sieved) on an electromagnetic sieve apparatus (Filtra FTL-0200, Badalona, Spain) with the same sieves used for the water-stable aggregate size distribution. A sieving time of 1 min and the lowest power program of the machine were used.

SOC concentrations from the bulk soil and from each water-stable aggregate size-class were determined using the wet oxidation of the Walkley–Black method described by Nelson and Sommers (1996). In some treatments the amount of large macroaggregates (2–8 mm) was not enough to determine SOC concentration. Consequently, large (2–8 mm) and small (0.250–2 mm) macroaggregates were mixed and SOC was determined as macroaggregate-C. The method was modified to increase the digestion of SOC. The modification consisted extensive heating of the sample during the digestion, boiling the sample at 150 °C for 30 min (Mebius, 1960).

In each chronosequence phase, the stratification ratio (SR) was calculated dividing the SOC concentration in the 0–5 cm soil depth by those in the 5–10 cm, 10–20 cm and 20–30 cm soil layers (Franzluebbers, 2002). Regression analyses were performed between the SR of SOC and the number of years under NT to assess the changes of this ratio over time and between SOC concentration and the proportion of water-stable aggregate fractions.

The data were analyzed using the SAS statistical software (SAS institute, 1990). To compare the effects of tillage treatments and soil depths, analysis of variance (ANOVA) for a randomized design was performed using the procedure general linear model. When significant, differences among treatments and depths were identified at the 0.05 probability level of significance using Duncan's test.

Table 1
Total soil organic carbon (SOC) concentration in the 0–30 cm soil depth in a no-tillage (NT) chronosequence with the following phases: conventional tillage (CT) and NT under 1 (NT-1), 4 (NT-4), 11 (NT-11) and 20 (NT-20) years.

Soil depth (cm)	SOC (g kg^{-1})				
	CT	NT-1	NT-4	NT-11	NT-20
0–5	11.9 (0.3)‡ cA*¶	10.5 (0.5) cAB	17.3 (1.7) bA	24.0 (1.2) aA	24.0 (0.6) aA
5–10	11.7 (0.4) AB	12.1 (2.1) A	13.0 (1.2) B	15.0 (3.5) B	14.1 (1.6) B
10–20	10.3 (1.9) AB	11.0 (1.1) AB	9.3 (0.9) B	8.8 (0.8) C	9.0 (1.3) C
20–30	9.9 (0.4) B	8.6 (1.7) B	8.5 (2.1) B	7.1 (0.9) C	6.5 (2.3) C

*Within each depth values are significantly different between chronosequence phases at P<0.05.
¶Within each chronosequence phase, different letters indicate significant differences between depths at P<0.05.
‡Values in parenthesis are the standard errors of the mean.