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Beneficial effects of reduced tillage and green manure on soil aggregation and stabilization of organic carbon in a Mediterranean agroecosystem

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ABSTRACT

Semiarid Mediterranean agroecosystems need the implementation of sustainable land management (SLM) practices in order to maintain acceptable levels of soil organic matter (SOM). The application of SLM practices helps to maintain soil structure and physical-chemical protection of soil organic carbon (SOC), hence improving soil carbon sequestration and mitigating CO_2 emissions to the atmosphere. In an organic, rain-fed almond (*Prunus dulcis* Mill., var. Ferragnes) orchard under reduced tillage (RT), as the habitual management practice during the 14 years immediately preceding the experiment, we studied the effect of two agricultural management practices on soil aggregate distribution and SOC stabilization after four years of implementation. The implemented practices were (1) reduced tillage with a mix of *Vicia sativa* L. and *Avena sativa* L. as green manure (RTG) and (2) no-tillage (NT). Four aggregate size classes were differentiated by wet sieving (large and small macroaggregates, microaggregates, and the silt plus clay fraction), and the microaggregates occluded within small macroaggregates (SMm) were isolated. In addition, three organic C fractions were separated within the small macroaggregates and microaggregates, using a density fractionation method: free light fraction (free LF-C), intra-aggregate particulate OM (iPOM-C), and organic C associated with the mineral fraction (mineral-C). The results show that the combination of reduced tillage plus green manure (RTG) was the most-efficient SLM practice for SOC sequestration. The total SOC increased by about 14% in the surface layer (0–5 cm depth) when compared to RT. Furthermore, green manure counteracted the effect of tillage on soil aggregate rupture. The plant residue inputs from green manure and their incorporation into the soil by reduced tillage promoted the formation of new aggregates and activated the subsequent physical-chemical protection of OC. The latter mechanism occurred mainly in the fine iPOM-C occluded within microaggregates and mineral-C occluded within small macroaggregates fractions, which together contributed to an increase of up to 30% in the OC concentration in the bulk soil. No-tillage favored the OC accumulation in the mineral-C within the small macroaggregates and in the fine iPOM-C occluded within microaggregates in the surface layer, and in the mineral-C occluded within the small macroaggregates and microaggregates at 5–15 cm depth, but four years of cessation of tillage were not enough to significantly increase the total OC in the bulk soil.

1. Introduction

Agriculture plays a major role in the global fluxes of carbon dioxide and has been promoted as a partial means for slowing further increases in greenhouse gases (GHG), through the potential for soil C sequestration in cropping systems under suitable management practices (Robertson et al., 2000). In the last decade, there has been increasing policy interest in reducing GHG emissions from agriculture (UNFCCC, 2008). Policy makers face a challenge to develop and implement effective GHG abatement strategies for agriculture, which requires identification of the best management practices for each agroecosystem. In particular, there is a need for better knowledge of the effects of different agricultural practices on C sequestration and on the mechanisms of C stabilization (Six et al., 2002; De Gryze et al., 2004), particularly in semiarid areas and under rain-fed agriculture.

The amount of plant residues and the degree of soil organic carbon decomposition are vital factors in the formation and

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stabilization of aggregates, which in turn improve soil structure and drive soil organic carbon (SOC) sequestration (Haynes and Beare, 1996). However, the mechanisms of the interaction between the soil structure and SOC dynamics are still not well understood (Blanco-Canqui and Lal, 2004). It is known that agricultural management practices modify the soil structure, with subsequent profound impacts on soil carbon sequestration. In agricultural soils, tillage and traffic operations are major factors involved in soil structure degradation, due to aggregate disruption, with the loss of aggregate-occluded SOC through fragmentation and compaction processes (Paustian et al., 1997a). In fact, the negative effects of conventional tillage and the benefits of using conservation agriculture measures (such as conservation crop rotations, reduced tillage, cover crops, and no-tillage), in terms of SOC sequestration, as well as suitable techniques for GHG mitigation, have been demonstrated widely (Paustian et al., 1997b; Abdalla et al., 2014).

No-tillage (NT) is one of the conservation agriculture measures that have been applied in the last three decades all over the world in order to maintain or increase the stock of organic carbon in soil and mitigate CO_2 emissions (Dimassi et al., 2014). However, its beneficial effects on SOC stocks have not been always proved, and contrasting results have been reported due to different methodological approaches, soil depth considered, years of no tillage implementation, etc. (Powlson et al., 2014). Green manure incorporation has also been demonstrated to improve the soil structure and increase SOC accumulation (Higashi et al., 2014; Poeplau and Don, 2015), besides helping to control erosion (Almagro et al., 2013). Nevertheless, it is not a common practice in semiarid agroecosystems because of a fear of competition over water resources between the green manure and the main crop (Unger and Vigil 1998; Martínez-Mena et al., 2013). Most of the experimental studies focused on the impacts of agriculture management practices on SOC dynamics have been performed under extensive cereal and irrigated crops in temperate (Virto et al., 2011; Dimassi et al., 2014) or Mediterranean areas (Álvaro-Fuentes et al., 2009; Macinelli et al., 2010; López-Garrido et al., 2014). However, very few studies have been carried out under rain-fed tree crops in semiarid areas – where these crops represent a significant proportion of the total agricultural production (Nieto et al., 2012; Almagro et al., 2013). Moreover, only a few studies were orientated to determine the effects of the conservation agriculture practices on SOC pools and to elucidate how OC interacts physically and chemically with aggregates as well as with mineral particles. In fact, the physical protection of OC by aggregates (Denef et al., 2001, 2007) and the physical-chemical stabilization through the adsorption and chemical binding of OC onto mineral surfaces are considered to be important mechanisms of soil OC stabilization (Krull et al., 2003; Marschner et al., 2008; Garcia-Franco et al., 2014). The study of different SOM fractions (free light fraction, intra-aggregate particulate OM, and OC associated with the mineral soil fraction) within soil aggregates is a key element in the reliable assessment of soil C dynamics and can be used as an early indicator of soil changes caused by management practices (Six et al., 2002). The identification of these fractions will improve our understanding of how aggregates stabilize and store SOC (von Lützow et al., 2007; Du et al., 2015), helping us to select the best sustainable land management (SLM) practices with regard to the enhancement of SOC sequestration in Mediterranean areas.

The general aim of this study was to assess the effectiveness of different SLM practices for enhancing soil C sequestration in semiarid agricultural areas, to promote changes in existing conventional agronomic practices from a climate change mitigation perspective. Specifically, the objectives were: (1) to assess the effects of reduced tillage, reduced tillage plus green manure, and no-tillage on soil aggregation and OC pools associated with different aggregate-size classes and (2) to gain insight into the C sequestration mechanisms in semiarid agroecosystems under different management practices. The following hypotheses were tested: (i) green manure promotes new C inputs and hence the OC associated with soil aggregates, (ii) the cessation of tillage reduces soil aggregate disruption and increases physical protection of SOC, and (iii) physical-chemical protection is the main mechanism responsible for the accumulation of OC in these agroecosystems.

2. Material and methods

2.1. Site description and experimental design

The experimental area was established on 21 October 2008 in an organic, rain-fed almond (*Prunus dulcis* Mill., var. Ferragnes) orchard located in Cehegín, in the Northwest of the province of Murcia, in Southeast Spain (38°3′15″N, 1°46′12″W). The altitude of the orchard is 633 m a.s.l. and the average slope is lower than 7%. The climate is semiarid Mediterranean with an average annual precipitation of 370 mm, concentrated in the spring and autumn months, but with great inter- and intra-annual variability. The mean annual temperature is relatively high, 16.6 °C, and the mean potential evapotranspiration reaches 800 mm year^{-1}, so the mean annual water deficit, calculated by the Thornthwaite method, is 430 mm. July and August are the driest months. These conditions result in an aridic soil moisture and a thermic soil temperature regime. The soil is a *Petrocalcic Calcisol* (WRB, 2006) with the following main properties for the 0–30 cm soil layer: pH (H_2O, 1:5): 8.8 ± 0.2; electrical conductivity (1:5): 168.3 ± 23.3 μS cm^{-1}; carbonates percentage: 54.2 ± 11.5%; percentage of exchangeable calcium: 18.9 ± 0.2%; sand (2000–50 μm), silt (50–2 μm), and clay (<2 μm) contents: 430 ± 120 g kg^{-1}, 415 ± 90 g kg^{-1}, and 155 ± 42 g kg^{-1}, respectively; and a mixed-clay mineralogy constituted by an inter-stratified illite-montmorillonite as the major component, accompanied by kaolinite and illite.

For 14 years (the plantation age), the habitual soil management in the study area was reduced tillage (RT) to control weeds. In 2008, two different SLM practices were applied: (i) reduced tillage plus green manure (RTG) and (ii) no-tillage (NT). The experimental design consisted of nine plots (49 m length and 7 m width) in a randomized-block design, with three replicates for each treatment. Each plot comprised seven almond trees: the five central trees were used for all plant and soil measurements and the other two trees constituted guard rows (a buffer zone to avoid edge effects). Trees were planted in rows with 7 m × 7 m spacing. The tillage affected the whole plot area, including the area around the trunk base. The reduced tillage consisted of chisel plowing to 0.15 m depth using a cultivator, twice a year (autumn/spring), to control weeds. In this treatment, weeds were the only vegetation present between rows. The green manure consisted of a mix of common vetch (*Vicia sativa* L.) and common oat (*Avena sativa* L.) in a proportion of 3:1, sown annually during early autumn at 150 kg seeds ha^{-1} and mowed in May. After manually mowing, it was incorporated into the soil using a cultivator. In the NT treatment, annual and perennial vegetation growing between rows were manually mowed in May and left on the soil surface. No addition of OM or manure was performed.

2.2. Soil sampling and analysis

Soil samples were collected from three soil layers (0–5, 5–15, and 15–30 cm) in October 2012, following crop harvest. The soils were sampled in the rows between the trees, 3.5 m from the tree trunk. Two composite soil samples (each one from 5 sub-samples) were taken in each treatment, per block and depth, (2 replicates × 3 treatments × 3 depths × 3 blocks). A total of