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Carbon saturation and assessment of soil organic carbon fractions in Mediterranean rainfed olive orchards under plant cover management

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ABSTRACT

Olive groves are undergoing a marked change in the way that inter-row land is managed. The current regulation and recommendation encourages the implementation of plant cover, mainly to improve soil fertility and reduce erosion. However, there is no quantitative information on the dynamics and pools of soil organic carbon (SOC) fractions of different protection levels of the plant-residue-derived organic carbon (OC). This study was conducted to provide a range of annual OC inputs in commercial olive oil groves under natural plant cover, to assess the influence of the annual application of aboveground plant cover residues on unprotected and physically, chemically and biochemically protected SOC. In addition, we tested the carbon saturation hypothesis under plant cover. Ten olive oil orchards under plant cover management (PC), together with five comparable bare soil olive oil orchards (NPC) were selected and annual aboveground natural plant residues and SOC pools were sampled and quantified. Annual aboveground plant cover biomass and OC production in PC olive orchards averaged 1.48 t dry-weight (DW) ha^{-1} and 0.56 t C DW ha^{-1}, respectively with a great variability among sites (coefficient of variation of about 100%). SOC concentration in PC orchards was, on average, 2.8 (0–5 cm soil) and 2.0 (5–15 cm) times higher than in bare soils of NPC, and the pool of protected SOC in the top 15 cm was 2.1 times higher in the PC (17.9 mg C g^{-1} ± 5.7) (± standard deviation) compared to NPC (8.5 mg C g^{-1} ± 2.9) olive orchards. Linear or saturation type relationships between each SOC fraction and total SOC content for the range of SOC of the commercial olive oil orchards were statistically indistinguishable, and thus linear models to predict SOC accumulation due to plant cover in olive orchards are suitable, at least for the studied range of SOC. Overall, at regional scale where olive oil groves represent a very high proportion of the agricultural land, the use of plant cover appears to be a promising practice that promotes protection of the SOC, thus improving SOC sequestration.

1. Introduction

Soils are the largest carbon (C) reservoir of the terrestrial C budget (Lal, 2004), representing about 2500 Pg C (1500 of soil organic carbon and 950 of inorganic forms) (Lal, 2008). Therefore, even a relatively small increase or decrease in soil C content due to changes in land use or management practices may result in a significant net exchange of C between the soil reservoir and the atmosphere (Houghton, 2003). Conversion of natural ecosystems to agroecosystems causes a significant depletion of the soil organic carbon (SOC) pool (Lal, 2004), mainly because C output exceeds the input and this is exacerbated when soil degradation is severe. Therefore, agricultural soils have the potential to sequester C from the atmosphere with proper management. Thus, policy makers face the challenge of developing and implementing effective SOC accretion strategies for agriculture, which requires identification of the best management practices for each agroecosystem. A number of agricultural management strategies are known to sequester soil C by increasing C inputs to the soil and enhancing various soil processes that protect C from microbial turnover. However, uncertainties about the extent and permanence of C sequestration in these systems remain (Six et al., 2002).

Most experimental studies to date have focused on the impacts of

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specific agricultural 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; Lopez-Garrido et al., 2011). However, very few studies have been carried out under rain-fed tree crops in semiarid areas, such as olive oil orchards, where these crops represent about 60% of the total olive orchard surface (e.g. Nieto et al., 2013).

The incorporation of cover crops (i.e. green manure) into the soil of a given cropping system is considered a promising sustainable management practice to reduce soil erosion risk (Alliaume et al., 2014; Francia-Martínez et al., 2006; Gómez et al., 2009), while compensating soil C losses derived from land-use change and tillage in agricultural fields (Gómez-Muñoz et al., 2014; Milgroom et al., 2007; Ramos et al., 2010). This is an important issue in Southern Spain, where regional authorities introduced a policy of Good Agricultural and Environmental Practice in olive farming, which consists of linking the subsidy for cultivating the olive crop to the requirement of provide/permit additional cover plants under certain circumstances (e.g. mean slope over 7%).

Plant cover in olive oil orchards is mainly comprised of natural vegetation which is allowed to emerge spontaneously in autumn and winter along the middle of the orchard lanes, covering up to approximately one-third of the surface. The plant cover should be eliminated in late March or early April, before it starts competing for water and it is then usually disrupted, mainly by mechanical mowing and/or herbicides. Plant residues may be left on the soil surface or mechanically mixed into the top centimetres of soil by tillage. Both approaches are currently used and are realistic land management options. Most previous studies related to the effectiveness of cover plants in olive orchards have been designed to evaluate the effects of this practice in mitigating soil erosion (e.g. Gómez et al., 2004), but to a lesser extent to evaluate the dynamics of C cycling associated with it (Castro et al., 2008). Vicente-Vicente et al. (2016) recently found that plant cover in woody crops (olive and almond orchards and vineyards) significantly contributed to SOC accumulation with annual rates averaging 1.1 t C ha^{-1}.

The amount of plant residue and the degree of SOC decomposition are key factors in the formation and stabilization of aggregates, which in turn improve soil structure and drive SOC sequestration (Haynes and Beare, 1996). However, no studies in olive groves have been done to determine the effects of plant covers on different SOC pools and to elucidate how SOC interacts physically and chemically with aggregates, as well as with mineral particles.

The physical protection of organic carbon (OC) by aggregates (Denef et al., 2001, 2007) and the physico-chemical stabilization are considered to be important mechanisms of SOC stabilization (Krull et al., 2003; Marschner et al., 2008; Garcia-Franco et al., 2014). The study of different protected SOC fractions 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), helping us to select the best sustainable land management practices with regard to the enhancement of SOC sequestration in Mediterranean areas.

On the other hand, according to the theory of soil C saturation proposed by Stewart et al. (2007), the potential for SOC stabilization has a limit, and as the SOC approaches its saturation level, the increase in SOC stock becomes smaller despite increasing C input rates. Stewart et al. (2007) found that SOC saturation does occur, but that it is not always seen in agricultural field experiments since the range of C input levels is often too small for saturation to be shown. Several other studies also support the theory that soils can become C saturated (Chung et al., 2008; Six et al., 2002).

The role of plant cover in fruit tree cropping systems on SOC sequestration at regional scale might require the use of models. The elucidation of linear or saturation relationships across a typical range of C inputs, due to the presence of plant cover and protected SOC fractions, is important to accurately predict the potential for C sequestration under this management.

We hypothesized the following: (1) Spontaneous plant cover increases the total SOC content compared to the non-cover management; (2) this increase is mainly due to an increase in the most labile SOC fractions; and (3) there is a maximum capacity limit for SOC accumulation for some fractions, especially those related to the silt and clay content.

The main purpose of this study was to assess the effectiveness of plant cover for enhancing soil C sequestration in semiarid rain-fed olive oil orchards, to promote changes in existing conventional agronomic practices from a climate change mitigation perspective. Specifically, the objectives were: (1) to determine the variability of annual aboveground OC input due to the presence of a plant cover; (2) to assess the effects of plant cover residue addition to the soil on SOC accretion and SOC fractions of different protective levels (unprotected and physically, chemically and biochemically protected); and (3) to elucidate if the relationship between total SOC and SOC fractions follows a linear or a saturation curve over the range of SOC measured.

2. Material and methods

2.1. Site description and experimental design

Ten olive orchards, in which a plant cover (PC thereafter) was left to grow in the inter-row area each year during the last twelve years, were selected in different sites (CA1, CA2, CT, MO, LO, DE1, DE2, PE, JA and AL) of Jaén and Granada provinces (Andalusia, southern Spain) in soils over marls with the same parent material. Mean annual precipitation in the area was 446 mm (average value from different meteorological stations in Granada and Jaén locations) about 10% less than the 25-y average. Aboveground plant cover biomass in all orchards was mechanically mowed each year during March and plant residues were left on the soil surface. Typically, plant cover comprised between 30 and 60% of the whole olive oil farming area. Soils in these orchards differed in a range of characteristics, some of which are shown in Table 1. Five out of the ten PC olive orchards were paired with a nearby (within a distance of tens of metres) comparable olive orchard (in terms of climate, orientation, slope, soil properties and farming characteristics such as tree density and age), except for the lack of plant cover during at least the last 12 years. In these olive orchards with bare soil (NPC, thereafter), plants were controlled by mechanical mowing and/or applying pre-emergence herbicides in the autumn. Thus, differences between these five pairs of olive oil farming were attributed primarily to the presence or absence of the plant cover during autumn to the end of March and to the management related to the control of plants. All olive orchards presented a tree density of between 90 and 120 trees per hectare, aged 35–45 years, and trees were distributed in a regular arrangement typical of fruit trees, with a canopy cover typically of between 40 and 70% of the orchard area.

2.2. Soil and aboveground plant cover biomass sampling

In each of the ten PC olive orchards, aboveground annual plant cover biomass produced in 2010 was randomly determined several days before mowing (between the end of March to early April) by randomly throwing five woody frames (50 cm × 50 cm) in the inter-row area and subsequently measuring the dry weight of the aboveground plant biomass collected.

Soil below the frames used to collect aboveground cover plant biomass was also sampled. At each of the sampling point, a 50 cm × 50 cm pit was opened and soil samples were taken at depths of 0–5 and 5–15 cm. In the NPC olive orchards, 0–5 cm and 5–15 cm deep soils of the inter-row area were collected in the same day and in the same way that comparable PC olive orchards. Soil samples were