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The potential of reducing tillage frequency and incorporating plant residues as a strategy for climate change mitigation in semiarid Mediterranean agroecosystems

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A B S T R A C T

Improved soil management in rainfed Mediterranean agroecosystems can be a powerful strategy to mitigate the current atmospheric CO_2 increase, through soil carbon sequestration and stabilization. In this work, we assess the effects of different soil management practices (conventional tillage, CT, reduced tillage, RT, reduced tillage plus green manure, RTG, and no tillage, NT) on soil CO_2 flux dynamics and carbon sequestration in two organic rainfed almond (*Prunus dulcis* Mill.) orchards under semiarid conditions. Soil CO_2 flux, temperature, and moisture were measured monthly over two-three years, and shortly after tillage operations. The soil aggregation distribution (including micro-aggregates occluded within macro-aggregates) and associated organic carbon content were measured after four years of implementation. No significant differences in CO_2 emissions among the soils subjected to the distinct management practices were observed at either site. On the one hand, shifting from CT to RT or RTG increased the OC content by 56% on average in all aggregate sizes. On the other hand, suppressing tillage only increased the OC content (by 24%) in the macro-aggregates. Moreover, improved soil management practices modulated the response of soil CO_2 flux to temperature and moisture in these semiarid Mediterranean agroecosystems. According to our results, soil CO_2 flux under the conventional tillage treatment was more sensitive to temperature increments than with the reduced tillage treatments, indicating that bare soils will be more vulnerable to organic carbon mineralization with ongoing global warming. On the contrary, the incorporation of plant residues under the reduced tillage treatments promoted soil aggregation and organic carbon preservation, making soils more resilient to abrupt changes in temperature and moisture under these treatments.

1. Introduction

Agriculture and associated land-use changes contribute ~25% of total global anthropogenic greenhouse gas (GHG) emissions (Paustian et al., 2016), being CO_2 responsible for 50% of averaged annual GHG emissions for the 2000–2009 period (Smith et al., 2014). Since soils account for the majority (37%; mainly as N_2O and CH_4) of agricultural emissions (Tubiello et al., 2015), the adoption of improved soil management practices can be a powerful mitigation strategy, decreasing GHG emissions and sequestering carbon in agroecosystems while avoiding the conversion and degradation of natural ecosystems containing much greater soil carbon stocks than agricultural ones (Paustian et al., 1997; Smith, 2012). In addition, improved soil management can yield powerful synergies, such as i) maintenance of soil fertility and nutrient cycling, ii) prevention of soil erosion and water contamination, iii) increased soil water infiltration and storage capacity, and iv) making agroecosystems more resilient against the impacts of climate change (Almagro et al., 2016; German et al., 2016; Palm et al., 2014; Smith, 2012; Stavi et al., 2016).

In agricultural systems, increased net soil carbon storage can be achieved by enhancing organic matter inputs (*i.e.*, plant residues, green manure, or other organic waste), by reducing decomposition rates (*i.e.*, by minimizing soil disturbance through no-tillage, tilling at a shallower depth, or reducing tillage frequency), or by the combination of both approaches (Paustian et al., 1997). But the efficiency of these approaches strongly depends on prevailing local conditions (temperature and moisture regimes, soil characteristics) and the legacy effect of historical management, and therefore varies from region to region. The soil CO_2 flux regulates the extent to which carbon that is incorporated or left on the soil surface as plant residues is retained in the soil.

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Therefore, understanding the effect of improved soil management on soil carbon fluxes and their environmental drivers can help us to manage more efficiently the flows of carbon in Mediterranean agricultural soils within a climate change context.

The importance of improved soil management practices in the mitigation of the current atmospheric CO_2 increase through the enhancement of soil organic carbon (SOC) levels has long been recognised (Aguilera et al., 2013; De Gryze et al., 2011; Paustian et al., 2016; Poeplau and Don, 2015), but a proper understanding of the response of Mediterranean soils to climate change and their mitigation capacity, if managed sustainably, is still lacking. Despite much research on soil CO_2 flux dynamics in relation to improved soil management in Mediterranean and other dry environments (Abdalla et al., 2016; Álvaro-Fuentes et al., 2007; Carbonel-Bojollo et al., 2011; González-Sánchez et al., 2012; González-Ubierna et al., 2014; Morrel et al., 2010), few studies have been conducted in woody cropping systems (but see Montanaro et al., 2016) and it is not yet clear which factors control the total amount of carbon released to the atmosphere and its implications for the SOC balance. Woody cropping systems differ from annual or perennial herbaceous ones in many aspects that can be relevant for soil carbon dynamics and its responses to improved management. Because woody cropping systems are widely cultivated on steep slopes and marginal lands, the soils under these systems usually have a lower fertility and a higher stone content compared to those under herbaceous rotations. In addition, differences in management among them can lead to different annual C inputs derived from pruning or plant residues (Aguilera et al., 2013a).

In previous studies, we demonstrated the potential of reducing tillage frequency and incorporating plant residues into the soil for climate change mitigation in semiarid Mediterranean ecosystems through SOC sequestration (Garcia-Franco et al., 2015; Almagro et al., 2016). From these results, new research questions arose regarding the effect of improved soil management on soil carbon fluxes and their environmental drivers. The main purpose of this study was to assess the soil CO_2 flux dynamics and its response to soil temperature and water content under several soil management practices differing in tillage frequency and plant residue management, for two organic rainfed almond orchards with similar climatic conditions but different land management history. Specifically, we aimed to: i) characterize the short-term response of soil CO_2 flux to tillage operations and its implications for annual soil CO_2 emissions; ii) examine if the response of soil CO_2 flux to soil temperature and volumetric water content differs among soil management practices; and iii) assess the effect of improved soil management practices on SOC stabilization. We hypothesize that changes in soil environmental conditions driven by improved soil management will modulate the response of soil CO_2 flux to increments in soil temperature and moisture fluctuations, making Mediterranean agricultural soils more resilient to the forecasted climate change.

2. Material and methods

2.1. Study sites

Our study was conducted in two organic rainfed almond (*Prunus dulcis* Mill.) orchards located in the northwest (Cehegín, 38°3′15″N, 1°46′12″W; 633 m a.s.l., hereafter referred to as “Burete”) and centre (Zarzadilla de Totana, 37°51′59″N, 1°43′11″W; 839 m a.s.l., hereafter “Alhagüeces”) of the province of Murcia, in southeastern Spain. At both sites, trees are in rows with a 7 m × 7 m spacing and no fertilizers were applied during the study. Both sites are characterized by a semiarid Mediterranean climate, with warm, dry summers and cold, relatively wet winters. The annual precipitation averages 370 mm (Burete) and 284 mm (Alhagüeces; 2000–2015; SIAM) and it is concentrated in the autumn and spring months, but with great inter- and intra-annual variability. The annual temperature averages 16 °C (Burete) and 15 °C (Alhagüeces). The mean potential evapotranspiration at both sites reaches 1200 mm yr^{-1} (calculated by the Thornthwaite method), so the mean annual water deficit is around 900 mm.

The two experimental sites are located on relatively shallow soils (average soil depth is about 30 and 45 cm at Burete and Alhagüeces, respectively) with moderate southeast-facing slopes of around 7% (Burete) and east-facing slopes ranging from 5% to 15% (Alhagüeces). The soils at both sites are classified as Calcisols (FAO, 2006) and have a silt-loam texture, high contents of $CaCO_3$ (~45%), a pH (H_2O, 1:5) of 8.7, and an electrical conductivity of 140 ± 2.8 μS cm^{-1}. Before the experiments were established, the SOC, nitrogen, and phosphorus concentrations at 0–30 cm depth were lower at Burete (13.1 ± 0.7, 0.12 ± 0.04, and 0.01 ± 0.00 g kg^{-1} soil, respectively) than at Alhagüeces (17.3 ± 1.1, 0.20 ± 0.04, and 0.04 ± 0.01 g kg^{-1} soil, respectively), presumably because of the previous land management (e.g., pig slurry amendment for about 10 years) at the latter.

2.2. Experimental design

Soil management practices were implemented in October 2008 at the two organic rainfed almond orchards. At Burete, reduced tillage (RT), the most common soil management practice among farmers in this area, was used as the reference (control) treatment and compared to reduced tillage plus green manure (RTG) and to no tillage (NT). At Alhagüeces, however, conventional tillage (CT) was compared to RT and to RTG. The tillage affected the whole plot area, including the area around the trunk base, and consisted of chisel plowing to 15 cm (at Burete) or 20 cm (at Alhagüeces) depth. The main differences among these soil management practices consist of the number of passes, the presence or not of plant cover in the rows, the quantity and quality of plant residues returned to the soil, and whether these are incorporated into the soil or left on the soil surface. Under CT, there is a lack of plant cover in the rows all-year-round, given that these almond fields are generally plowed between three and five times per year, following important rainfall events. By contrast, with both reduced tillage (RT and RTG) treatments as well as the NT treatment, a significant plant cover is noticeable at the end of the growing season, since these fields are plowed only twice a year (spring and fall) or are not tilled at all, respectively (Fig. S1). The RT treatment is dominated by annual and perennial grasses (*Hordeum murium* L., *Lolium perenne* L., and *Eruca versicaria* (L.) Cav.) that grow from mid-fall to late spring, when they are incorporated into the soil by plowing. The green manure consisted of a mixture of common vetch (*Vicia sativa* L.) and common oat (*Avena sativa* L.; at Burete) or barley (*Hordeum vulgare* L.; at Alhagüeces) in a 3:1 ratio at 150 kg ha^{-1}, which was sown during early fall and incorporated into the soil by plowing with a chisel plow in May. In the NT treatment, perennial grasses such as *Teucrium capitatum* L. and *Dactylis glomerata* L. are present from early fall to late spring, when they are cut off and left on the soil surface.

The experimental design consisted of nine plots (49 m long and 7 m wide) in a randomized-block design, with three replicates for each management practice. 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).

2.3. Soil CO_2 flux, temperature, moisture and precipitation measurements

The rates of soil CO_2 emission to the atmosphere were measured *in situ* with a Licor 8100 closed chamber system (LI-COR, Lincoln, NB, USA). For each management practice treatment, four PVC circular collars (5 cm deep, 10 cm in diameter) were inserted into the soil surface in the inter-tree locations, 3.5 m from the tree trunks. Soil CO_2 flux was measured monthly, from May 2012 to December 2014 (at Burete), and from February 2013 to December 2014 (at Alhagüeces), and always between 10:00 and 13:00, as it was shown previously that midday values of CO_2 flux are representative of daily averages (Davidson et al.,