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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Abstract

Here, we assess the effects of different soil management practices (conventional tillage, reduced tillage, reduced tillage plus green manure, and no tillage) 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. Moreover, improved soil management practices enhanced the organic carbon content in aggregates of all sizes and 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 mineralization with global warming. However, plant residues incorporation promoted soil aggregation and organic carbon preservation, making soils more resilient to abrupt changes in temperature and moisture.

Keywords: Improved soil management; Green manure; Almond orchards; Soil CO2 emissions; Carbon sequestration; Occluded micro-aggregates.

Introduction, scope and main objectives

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), 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), 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. The main purpose of this study was to compare the soil CO_2 flux dynamics and carbon sequestration performance of 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) assess the effect of improved soil management practices on SOC stabilization; and iii) examine if the response of soil CO_2 flux to soil temperature and water content varies among soil management practices. We expect that the adoption of improved soil management practices will enhance the carbon sequestration capacity of Mediterranean agricultural soils. We also 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.

Methodology

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. Simultaneously with the soil CO_2 flux measurements, the soil temperature (T) and volumetric soil water content (SWC) were measured at the 0-12 cm depth interval, adjacent to each soil collar. Soil temperature was automatically recorded with a LI-8100 soil temperature probe, and soil water content was measured using a FDR soil moisture sensor (HOBO event, 12 cm in length, Massachusetts, USA). The total plant biomass production – green manure or spontaneous annual and perennial grasses – was collected in May from four quadrants (1 m x 1 m) placed randomly for each management treatment. Soil samples were collected from the plow layer following crop harvest in November 2012, four years after the management practices were implemented. Aggregate-size separation was carried out on each soil sample using a modified wet-sieving method adapted from Elliott (1986).] A series of three sieves (2000, 250, and 63 µm) was used to obtain four aggregate size classes: (i) large macro-aggregates (LM; > 2000 µm); (ii) small macro-aggregates (SM; 250-2000 µm); (iii) micro-aggregates (m; 63-250 µm); and (iv) silt plus clay-sized particles (s + c; < 63 µm). The protected micro-aggregates contained within the small macro-aggregates (SMm) were obtained using the micro-aggregate isolation method described by Six et al. (2000) and Denef et al. (2004). The organic carbon (OC) concentration was analyzed separately for each water-stable aggregate-size class, as well as for the micro- within macro-aggregates, using the elemental analyzer mentioned above, after soil carbonates had been eliminated using 2 M HCl. The SOC stocks (g m^{-2}) were calculated as a product of the OC concentrations, soil bulk density (corrected for rock fragments), and depth of the plow layer for each management treatment and site.

Results

Soil CO_2 flux rates in all management treatments varied significantly during the year, following changes in soil temperature during the fall, winter, and early spring, or changes in soil moisture during late spring and summer. Repeated-measures ANOVA revealed no significant differences in the soil CO_2 flux rates among management practices throughout the study period at either site. The flux rates increased significantly shortly after the winter and spring tillage operations at Burete, but they levelled-off one (in winter) or three (in spring) days after tillage. Immediately after the winter tillage, soil CO_2 flux increased by 60% on average for the reduced tillage (RT) and green manure (RTG) treatments. In spring, soil CO_2 flux increased by 68% and 46% on average for the RTG and RT treatments, respectively, during the first two days following tillage. The responses of soil CO_2 flux to temperature were similar among the soil management practices during the growing period. However, the response of soil CO_2 flux to soil moisture was affected by the soil management during the dry period. In particular, suppression of tillage led to a lower basal soil CO_2 flux rate and less responsiveness to soil moisture fluctuations at Burete, while soil CO_2 flux under the green manure treatment appeared to be less responsive to soil moisture fluctuations at Alhagüeces. The suppression of tillage increased the proportion of large and small macro-aggregates but did not enhance the OC content of any aggregate size. However, green manure incorporation increased the proportion of small macro-aggregates and micro-aggregates occluded within the small macro-aggregates (SMm), while enhancing the OC content in all aggregate sizes. At Alhagüeces, reduced tillage frequency combined with the incorporation of plant residues increased the proportion of micro-aggregates occluded within small macro-aggregates (SMm). In addition, the RT and RTG treatments gave a greater OC content in most aggregate sizes, with the exception of the silt plus clay fraction, compared to the CT treatment.

Table 1. SOC stocks, percentage of SOC change among control and improved soil management practices after four years of their implementation, carbon respired from soil , organic carbon mean residence time (MRT, yr^{-1}), and plant residue inputs, for each management practice and site.

Site	Treatment	SOC stock ($g\ m^{-2}$)	ΔSOC (%)	C respired ($g\ m^{-2}\ yr^{-1}$)	MRT (SOC:C respired)	Plant inputs ($g\ m^{-2}\ yr^{-1}$)
Burete	RT	2517	nd	492	5.1	78.6
	RTG	3703	47	492	7.5	128.8
	NT	2544	1	405	6.3	120.7
Alhagüeces	CT	4223	nd	399	10.6	negligible
	RT	5448	29	469	11.6	173.6
	RTG	5551	31	439	12.6	174.4

RT: reduced tillage; RTG: reduced tillage plus green manure; NT: no tillage; CT: conventional tillage; nd: not determined. SOC stocks at Burete were estimated based on an equivalent soil mass-depth basis.

Discussion

The magnitude and duration of soil CO_2 peaks upon tillage vary depending on the prevailing soil environmental conditions and the legacy effect of historical management (Calderón et al. 2000). At our study sites, both the magnitude and duration of the soil CO_2 peaks after tillage were similar to those observed elsewhere (Abdalla et al. 2016) and did not significantly affect the annual CO_2 emissions of our semiarid Mediterranean agroecosystems.

At Burete, green manure incorporation had enhanced the OC content in all aggregate sizes (by 48% on average) without increasing soil CO_2 emissions to the atmosphere (compared to RT). By contrast, the suppression of tillage did not enhance the amount of OC stored in the soil compared to that of the RT treatment despite greater annual plant biomass inputs and somewhat lower amounts of carbon released to the atmosphere annually for the former treatment (Table 1). At Alhagüeces, contrary to what has been reported previously, reducing the tillage intensity did not decrease the amount of carbon released annually to the atmosphere. However, the SOC content was increased by 41% on average by both reduced tillage treatments at this site. It can be explained by the greater carbon inputs resulting from the incorporation of plant residues over the four years for both reduced tillage which promote soil aggregation and the physical protection of OC by aggregates (Garcia-Franco et al. 2015).

Soil management modified the response of soil CO_2 flux to temperature and moisture. During the growing period, soil CO_2 flux was more responsive to temperature under conventional tillage than under both reduced tillage treatments, despite the lower SOC content in the former at Alhagüeces. This pattern has been observed previously in other semiarid agroecosystems (Li et al. 2013), and highlights both the importance of plant covers in buffering the response of soil CO_2 flux to increased temperature through shading, and the fact that OC is physically protected by newly formed aggregates under the RT and RTG treatments. Contrastingly, bare soils are directly exposed and therefore would be much more susceptible to mineralization with the forecasted increase in temperature.

At Burete, however, soil under no tillage showed the lowest basal CO_2 flux rates and less responsiveness to soil moisture fluctuations during the dry period. These results are consistent with previous studies reporting lower soil CO_2 flux rates under NT and are explained by: i) the low-quality organic matter inputs (i.e., higher C:N) returned to the soil from its perennial plant cover, compared to the annual plant cover present in the reduced tillage treatments (Table 1); ii) plant residues left on the soil surface, rather than incorporated into soil by plowing, are less susceptible to decomposition (Almagro and Martínez-Mena, 2014); and iii) changes in soil environmental conditions (Martínez-Mena et al. 2013) that limit microbial activity.

Conclusions

Tillage operations had a rapid but short-lived effect on soil CO_2 flux rates, with no significant influence on the annual soil CO_2 emissions. Although four years may not be enough to assess changes in SOC, the results from this study suggest a trend towards enhancing SOC sequestration by reducing tillage frequency and incorporating plant residues into the soil in these semiarid Mediterranean agroecosystems. Our results also show that improved soil management can modulate the response of soil CO_2 flux to temperature and moisture in semiarid Mediterranean agroecosystems. For the conventional (intensive) tillage treatment, soil CO_2 flux was more sensitive to temperature increments than under the reduced tillage treatments, indicating that bare soils (including fallow fields) will be more vulnerable to mineralization as global warming proceeds. However, plant residues incorporation promoted soil aggregation and organic carbon preservation, making soils more resilient to abrupt changes in temperature and moisture. These findings also emphasize the need for results derived from longer-term studies (> 10 years), as well as studies at larger spatial scales representing a wide range of climatic conditions, to fully understand the mitigation potential of improved soil management practices in semiarid agroecosystems under climate change.

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