Factors limiting SOC sequestration by no-tillage in Mediterranean agroecosystems

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Abstract
In Mediterranean areas, soil organic carbon (SOC) sequestration following the adoption of no-tillage (NT) may be affected by certain factors. In this study, the next three factors are presented and reviewed: (i) sequestration duration; (ii) soil depth distribution; and (iii) climate change impact. Sequestration duration was determined in a NT chronosequence established in 1990 in a conventional tillage field. Changes in SOC distribution along the soil profile were evaluated in three long-term tillage experiments established in 1987, 1989 and 1990, respectively. Climate change impact on SOC storage was evaluated with the Century model together with climate outputs from four climate change scenarios. The chronosequence showed that about 80% of the total SOC gained during the first 20 years after NT adoption occurred during the first 11 years. Furthermore, the three long-term tillage experiments showed that SOC gains under NT decreased with soil depth. The simulation of climate change conditions revealed that NT responded differently to climate change depending on the scenario selected. According to the findings of this study, the three factors reviewed should be taken into account in order to maximize the SOC sequestered and to evaluate the success of NT as a mitigation option in Mediterranean agroecosystems.

Keywords: Soil organic carbon sequestration; No tillage; Mediterranean agroecosystems; sequestration duration; climate change.

Introduction, scope and main objectives

In Mediterranean conditions, agriculture production is dependent on soil water availability for crop growth. Scarce annual rainfall together with high evaporation losses limit crop yields and determine the economical profit of the farm. Managing agricultural soils for soil water conservation has been a main motivation in these areas in which traditional practices based on intensive tillage and cereal monocultures have been carried out during decades. In certain Mediterranean areas, however, signs of change are being seeing in the practices adopted by farmers. In particular, the adoption of less disturbing tillage techniques is gaining popularity in some areas. These techniques have resulted interesting in terms of operation costs, reducing labour hours and tractor use, and also improving soil water conservation leading to the concomitant increase in crop yield and water use efficiency when intensive tillage is suppressed (Lampurlanés et al., 2016). The increase in crop growth derived from the adoption of reduced tillage (RT) or no-tillage (NT) techniques may also have a significant impact on soil organic carbon (SOC) stocks in these areas. Under NT crop residues are left on soil surface and slowly incorporated into the soil resulting in the build-up of SOC in surface soil layers. In Mediterranean areas this C enrichment process following the adoption of NT could be altered under certain situations limiting the potential of this technique for SOC sequestration and, thus, for atmospheric CO_2 mitigation. According to this, in this study we reviewed the factors limiting NT to sequester SOC in Mediterranean agroecosystems. The next three main factors are presented in this paper: (i) sequestration duration; (ii) soil depth distribution; and (iii) climate change impacts.

Methodology

Data presented in this study were obtained from different experimental fields and also from the use of modelling tools. All the experimental fields were located in a representative Mediterranean area located in NE Spain (Ebro river valley) where climate is characterized by low annual precipitation (250-450 mm) and mean annual temperatures ranging from 13 to 15 ºC. In this area, the most frequent soil types are Aridisols, Inceptisols and Entisols (Álvaro-Fuentes et al., 2011). Typical crops include winter cereals (mainly barley and wheat), grapes, olives and almonds.

Sequestration duration was determined in a chronosequence established in 1990 in a conventional tillage (CT) field in which mouldboard ploughing had been the main tillage implement for more than 40 years. From 1990 to 2010, different proportions of the CT field were converted to NT in different years. Thus, in 2010, the chronosequence included four NT areas with four different durations: 1, 4, 11 and 20 years and a remaining CT area (Álvaro-Fuentes et al., 2014). In summer 2010, SOC and soil bulk density were measured by triplicate in each chronosequence phase and at four soil depths (0-5, 5-10, 10-20 and 20-30 cm).

Changes in SOC distribution along the soil profile were evaluated in three long-term tillage experiments established in Selvanera (SV), Peñaflor (PN) and Agramunt (AG) in 1987, 1989 and 1990, respectively (Álvaro-Fuentes et al., 2008). The three experiments differed among them in the type of CT implement (subsoiling in SV and mouldboard ploughing in PN and AG) and mean annual precipitation (475, 330 and 270 mm in SV, AG and PN, respectively). In summer 2015, soil bulk density and SOC concentration were measured in the 0-5, 5-10, 10-20, 20-30 and 30-40 cm soil depths, to calculate SOC contents.

Climate change impact on SOC storage was evaluated with the Century model (Parton et al., 1988) together with climate outputs from the next two climate models: ECHAM4 and CGCM2, both forced with two IPCC scenarios (A2 and B2) (Álvaro-Fuentes and Paustian, 2011). The model was run during 90 years and the SOC predicted at the end of the simulation period was compared to the initial SOC level.

Results

SOC sequestration duration

The chronosequence showed that about 80% of the total SOC gained during the first 20 years after NT adoption occurred during the first 11 years (Table 1). During the first 11 years annual SOC sequestration rate was 0.43 Mg C ha^{-1} yr^{-1}. However, during the last 9 years (from year 11 to 20) SOC sequestration rate dropped to 0.12 Mg C ha^{-1} yr^{-1} (Table 1).

Table 1: Soil organic carbon (SOC) stock and SOC sequestration rate in the 0-30 cm soil layer in the different no-tillage (NT) chronosequence phases: 0-NT, 0 years under NT; 1-NT, 1 year under NT; 4-NT, 4 years under NT; 11-NT, 11 years under NT; 20-NT, 20 years under NT (Álvaro-Fuentes et al., 2014).

	0-NT	1-NT	4-NT	11-NT	20-NT
SOC stock (Mg ha^{-1})	33.0	33.2	35.1	37.7	38.8
SOC sequestration rate (Mg ha^{-1} yr^{-1})		0.20	0.47	0.43	0.29

SOC distribution with depth

In the three tillage experiments presented in Table 2, SOC gains under NT decreased with soil depth. The greatest amount of SOC sequestered was observed when only the upper 5 cm soil layer was considered. However, when the entire soil profile sampled (0-40 cm) was evaluated, NT only increased SOC levels in two out of the three field experiments, with SOC gains below 7%. In the SV site, indeed, SOC showed lower SOC contents in NT compared with CT when the entire 0-40 cm soil layer was considered (Table 2).

Table 2: Percentage of SOC gain in no tillage (NT) vs. conventional tillage (CT) in three long-term experiments (SV, Selvanera; AG, Agramunt; and PN, Peñaflor). Positive or negative values denote SOC gains or losses, respectively.

Soil depth (cm)	SV	AG	PN
0-5	40	128	71
0-10	15	90	48
0-20	-1	40	24
0-30	-9	12	13
0-40	-12	1	6

Climate change impact on SOC sequestration

Depending on the scenario selected, NT responded differently to climate change. Compared with the baseline scenario (current climate conditions), the annual SOC sequestration rate in NT slightly increased in the two CGCM2 scenarios (from 0.44 Mg C ha^{-1} yr^{-1} under baseline to 0.46 Mg C ha^{-1} yr^{-1} under climate change) but it decreased in the two ECHAM4 scenarios (from 0.44 Mg C ha^{-1} yr^{-1} under baseline to 0.38 Mg C ha^{-1} yr^{-1} under climate change), which corresponded to the climate scenarios with the greatest decrease in precipitation and the greatest increase in temperature predicted. Accordingly, the SOC contents at the end of the simulation period (i.e., 90 years) were 74.9, 76.0, 76.0, 70.2, 69.0 Mg C ha^{-1} in the baseline, CGCM2-B2, CGCM2-A2, ECHAM4-B2, ECHAM4-A2, respectively (data not shown).

Discussion

Despite NT has been recognized as an effective strategy to increase SOC stocks in Mediterranean agroecosystems, some aspects may limit its potential to sequester SOC as it has been demonstrated in this study. In our experiment, SOC increased over the first 20 years after NT adoption, similar to the findings reported by West and Six (2007), who concluded that climate, soil properties, land-use history and management mainly controlled sequestration duration. Tillage also impacted SOC allocation along the soil profile. The three long-term experiments selected in this study showed a decrease in SOC differences between NT and CT with soil depth. This finding has been discussed in several review papers (e.g., Baker et al., 2007; Powlson et al., 2011). Angers and Eriksen-Hamel (2008) recommended to sampling below 30 cm depth when NT is compared to CT. Finally, the Century ecosystem model predicted a significant impact of climate change on the ability of NT to sequester SOC in Mediterranean systems. The sign of the impact could vary depending on the final degree of future climate variation. The scenarios that promoted the highest rainfall reduction (ECHAM4 scenarios) resulted in the lowest sequestration rates due to their impact on crop growth and C inputs incorporated in the soil. However, climate change scenarios with small rainfall reductions (CGCM2 scenarios) had little impact on C inputs and they could even increase SOC sequestration rates compared with the baseline scenario due to a reduction in the decomposition rates (Álvaro-Fuentes and Paustian, 2011).

Conclusions

No tillage (NT) is an interesting option to sustain farm productivity and to decrease labour hours. Moreover, NT adoption is generally related to the increase of SOC stocks and, in turn, to the soil sink capacity to decrease atmospheric CO_2 concentration. In this study, we have identified three main factors that may limit the potential for SOC sequestration in Mediterranean soils: the sequestration duration, the distribution of SOC along the soil profile and the impact of climate change on SOC sequestration. These three factors should be taken into account in order to maximize the SOC sequestration and to evaluate the success of NT as a mitigation strategy in Mediterranean agroecosystems.

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