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LONG-TERM ORGANIC FARMING ON A CITRUS PLANTATION RESULTS IN SOIL ORGANIC CARBON RECOVERY

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ABSTRACT: *It has been shown that soil management under organic farming can enhance soil organic carbon, thereby mitigating atmospheric greenhouse gas increases, but until now quantitative evaluations based on long term experiments are scarce, especially under Mediterranean conditions. Changes in soil organic carbon (SOC) content were examined in response to organic management with cover crops in a Mediterranean citrus plantation using 21 years of survey data. Soil organic carbon increase was more apparent 5 years after a land management change suggesting that, for citrus plantations on Mediterranean conditions, studies should be longer than five years in duration. Soil organic carbon sequestration rate did not significantly change during the 21 years of observation, with values ranging from $-1.10 \text{ Mg C ha}^{-1} \text{ y}^{-1}$ to $1.89 \text{ Mg C ha}^{-1} \text{ y}^{-1}$. After 21 years, $61 \text{ Mg CO}_2 \text{ ha}^{-1}$ were sequestered in long-lived soil C pools. These findings demonstrate that organic management is an effective strategy to restore or increase SOC content in Mediterranean citrus systems.*

La agricultura ecológica a largo plazo en plantaciones de cítricos permite la recuperación del carbono orgánico del suelo

RESUMEN: *Se ha demostrado que el manejo del suelo bajo agricultura ecológica puede aumentar el contenido de carbono orgánico en el suelo moderando el incremento de los gases de efecto invernadero, pero hasta la fecha las evaluaciones cuantitativas basadas en mediciones a largo plazo han sido escasas, especialmente bajo condiciones mediterráneas. En esta investigación se examinaron los cambios en el contenido de carbono orgánico como respuesta a la agricultura ecológica con cobertura vegetal en una plantación de cítricos en el área mediterránea, utilizando una base de datos de 21 años. El incremento de contenido de carbono orgánico en el suelo fue más evidente tras cinco años desde el cambio del manejo del suelo, sugiriendo que, para plantaciones de cítricos en ambientes mediterráneos, los estudios deberían tener una duración superior a cinco años. La tasa de secuestro de carbono orgánico no cambió significativamente durante los 21 años de observaciones, con valores que oscilaron entre $-1.10 \text{ Mg C ha}^{-1} \text{ a}^{-1}$ y $1.89 \text{ Mg C ha}^{-1} \text{ a}^{-1}$. Tras 21 años, un total de $61 \text{ t CO}_2 \text{ ha}^{-1}$ fueron secuestradas en las áreas de acumulación de carbono en el suelo. Estos resultados demuestran que la agricultura ecológica es una estrategia efectiva para restaurar o incrementar los niveles de carbono orgánico en el suelo en los sistemas de cítricos mediterráneos.*

Key words: Organic carbon, citrus, long-term experiment, carbon sequestration rate.

Palabras clave: Carbono orgánico, cítricos, experimento a largo plazo, tasa de secuestro de carbono.

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1. Introduction

Organic farming has been suggested as a potential solution to achieve sustainable agriculture management given some of the hazards and environmental damage caused by the widespread use of agro-chemicals in the Green Revolution during the 20th century (Benbrook and McCullum-Gómez, 2009; Argyropoulos *et al.*, 2013; Seufert *et al.*, 2017). Organic farming is a strategy based in the use of natural products to achieve sustainable agriculture (Rigby and Cáceres, 2001). Organic farming is based in the natural cycles of nutrients, and avoids any use of chemicals that damage life, soils, water and air quality and is accepted even more widely by stakeholders (Michelsen, 2001). Organic farming can be practiced on any crop, and

in vineyards can help to achieve sustainable management (Kapović Solomun *et al.*, 2018; Wang *et al.*, 2018).

Soils are a key component of the Earth system as they mediate hydrological, erosional, biological and geochemical cycles (Davidson and Janssens, 2006; Gruber and Galloway, 2008). The importance of soils in the Earth system is widely recognized, and they underpin the delivery of many of the United Nations Sustainable Development Goals (Keesstra *et al.*, 2016a). Preserving soil is essential for sustainability, as soils provide vital functions to plants and animals, produce food, biomass and raw materials, habitat, maintain the gene pool, the carbon sink, and manage water, minerals and nutrient cycles (Smith *et al.*, 2015). The United Nations highlighted that soil protection is a key land-use policy issue and there is a need to develop strategies to maintain soil quality, soil functions and services to achieve sustainability (Keesstra *et al.*, 2016b, 2018; Panagos *et al.*, 2016; Paleari, 2017).

Previous research demonstrated that organic farming can improve soil quality, from a physical, chemical and biological point of view. Natural soil fertility can be enhanced by organic farming (Maeder *et al.*, 2002) and organic farming promotes below- and above-ground biota (Birkhofer *et al.*, 2008). A comparison of organic and conventional farming systems shows that the soil organic carbon (SOC) content and soil biology indicators were greater after 21 years of organic farming (Fließbach *et al.*, 2007). Different chemical and biological indicators demonstrated the positive impact of organic farming systems in Central Italy (Marinari *et al.*, 2006). Glover *et al.* (2000) applied a systematic rating method to determine soil quality in conventional, organic and integrated apple orchards, and Liebig and Doran (1999) measured the impact of organic practices on soil quality indicators. Schjonning *et al.* (2002) found that soil organic carbon increased in quality in humid sandy loam soils under organic agriculture. Most of these changes occur because organic farming improves soil fauna (Crittenden *et al.*, 2014) and natural soil fertility (Bowles *et al.*, 2014). Organic farming reduces soil losses and promotes the use of catch crops, mulches, weeds or chipped pruned branches (Kirchhoff *et al.*, 2017; Cerdà *et al.*, 2018a). Increased plant and litter input reduces losses of soil and SOC, and promotes soil fertility and soil resilience. This impact is based in the increase in SOC, which underpins many positive soil characteristics (Smith *et al.*, 2015). Macilwain (2004) suggests that organic farming can be the future solution for the improvement of agroecosystems. Organic farming also encourages natural pest control (Crowder *et al.*, 2010), and will likely improve agricultural sustainability (Reganold *et al.*, 2001). It has also been suggested that organic farming can transform agricultural soils into a sink of carbon as a way to reduce global warming (Skinner *et al.*, 2014). This idea has attracted political attention since 2016, when a new international initiative was launched by France to mitigate climate change by sequestering carbon in the form of SOC. It was argued that an additional 4 parts per thousand, or “4 per mille” of SOC per year would help reach the French climate change mitigation target and this is based on the high capacity that degraded soils have to sequester SOC (Averill *et al.*, 2014; Fujisaki *et al.*, 2015; Lehmann and Kleber, 2015).

Changes in SOC triggered by organic farming have been widely studied in temperate climates (Sommer and Bossio, 2014; Catalán *et al.*, 2016; Smith, 2016), but little is known in arid and semiarid climatic conditions. This is also true for the Mediterranean region which produces large amounts of citrus, vine, grapes, olive oil, fruits and vegetables that need a healthy soil with sufficient nutrients, normally supplied by the soil organic matter (Lugato *et al.*, 2014; Álvaro-Fuentes *et al.*, 2014; Schillaci *et al.*, 2017). However, due to intensive production over centuries, most soils are depleted in natural organic matter (Borrelli *et al.*, 2016; Montanaro *et al.*, 2017; Novara *et al.*, 2017). The current citrus production in Eastern Spain is modern, technical and uses large inputs of agrochemicals, and induce high erosion rates (Cerdà *et al.*, 2009) and low infiltration rates (Di Prima *et al.*, 2018). These systems need strategies to reduce the soil losses (Cerdà *et al.*, 2018b, 2018c; Keesstra *et al.*, 2019) and improve soil quality (Hondebrink *et al.*, 2017).

Citrus has been grown since the 19th century, and due to rising market prices in Europe, they were among the first systems to use seabird guano (manure) from Peru and natural Chilean sodium nitrate (Chile Saltpetre) for fertilization, though soon after, chemical fertilizers were introduced. Next to the success of the conventional citrus plantation, the development of the European Union regulations and incentives for organic farming in the 1990s resulted in the growth of organic farming, which now accounts for 3% of the citrus land, and is expected to grow in future due to favourable markets for organic products. The growth in organic citrus farming is an opportunity to increase the amount of carbon stored in the soil system and to reduce atmospheric CO₂, thereby contributing to the mitigation of climate change. Long-term measurements are necessary to understand the behaviour of natural systems (Novara *et al.*, 2019). To determine the evolution of soil carbon content, we measured SOC content in citrus orchards between 1995 and 2016. These long term measurements shed light on the evolution of SOC and the impact of land management on ecosystem services *via* carbon sequestration useful to provide information for establishing incentives, guidelines and environmental policies. Therefore, the aim of this study is to examine, under field conditions, the long-term changes of SOC under organic farming management in citrus orchards in a Mediterranean environment.

2. Material and methods

2.1. Study area and experimental design

This research was carried out at the Alcoleja Experimental Station located in the Cànyles river watershed in Eastern Spain (UTM: 709191X, 4316356Y; Zone 30), at 156 m.a.s.l.. The climate is Mediterranean with a mean annual precipitation of 545 mm and a mean annual temperature of 16 °C. The soil is a Xerorthent (Soil Survey Staff, 2014). The texture of the soil is a clay-loam, consisting of 19.8% clay, 42.1% silt, and 38.0% sand. A 1 ha research plot was selected with orange plantations (45 years old) of the Naveline variety (rootstock Cleopatra). The trees are planted at 5 x 4 m in distance and the plot is irrigated by flooding in summer every 21 days and during drought periods. The irrigation water comes

from a natural spring (Riu de Sants), though in summer, the water is pumped from the same aquifer when there is a shortage in the river discharge, which has been frequent since the 1980s due to aquifer depletion. The spring supplies the discharge for the irrigation and is 2 km from the experimental station. The studied soil was managed as a conventional (chemical) farm from the 1960s until 1994, when the orange trees were planted. Since 1995, organic farming management has been applied, with chipped pruned branches and weeds, and manure from sheep at an application rate of 15 Mg ha⁻¹ (0.06% N, 0.02% P₂O₅, and 0.07% K₂O) applied once per year in early spring (usually around March 19th). The soil was sampled each winter and summer at 0-1, 2-3, 7-8, 17-18, and 30-31 cm soil depth (10 replicas * 5 soil layers= 50 samples). The weeds were cut with a small hand-cutting machine and no heavy machinery was used as the space between trees does not allow heavy machinery to pass. Field-moist soil samples were sieved at 2 mm and stored at environmental temperatures; SOC content (g kg⁻¹) was determined using the Walkley and Black (1934) method for the duration of the experiment. Soil bulk density was measured with the ring method.

2.2. Data Analysis

Soil organic carbon sequestration rate (Mg ha⁻¹ yr⁻¹) for each soil layer was calculated as the ratio between SOC change during the long-term experiment and the duration (in years) of the experiment. The SOC stock difference between 1995 and 2016 was converted to CO₂ using stoichiometric ratio CO₂/C (3.667). After checking data normal distribution, statistical difference between the first (summer, 1995) and the last sampling data (winter, 2016) was checked by Tukey test for each sampling depth.

3. Results and discussion

3.1. Soil organic carbon under organic farming

Soil organic carbon stock in the 0-31 cm soil depth significantly increased after 21 years of organic farming management, ranging from 4.5 g kg⁻¹ in 1995 to 9.7g kg⁻¹ in 2016 (Fig. 1). The highest SOC content increase was in the top soil layer (0-1cm), ranging from 11.8 ± 1.3 g kg⁻¹ in 1995 to 55.3 ± 8.8 g kg⁻¹ in 2016 (Fig. 2). The first layer received more C input from litter, pruning residues, manure and spontaneous vegetation, leading to the large increase in SOC content. The rate of increase in SOC was lower during the first 5 years since organic farm conversion (Fig. 2). This suggests that the pruning residues and other organic inputs (weed biomass), which were not incorporated into the soil, need a period of about 5 years before they become part of the soil. After the first 5 years, the SOC showed a logarithmic increase in the first soil layer, which was not recorded in the deeper layer (Fig. 2). In addition, the soil under conventional farming had very few soil biota (Walmsley and Cerdà, 2017), which need time to recolonize the site that has been taken into organic production. This period of recolonization may also be the reason for the time lag of 5 years for change in SOC.

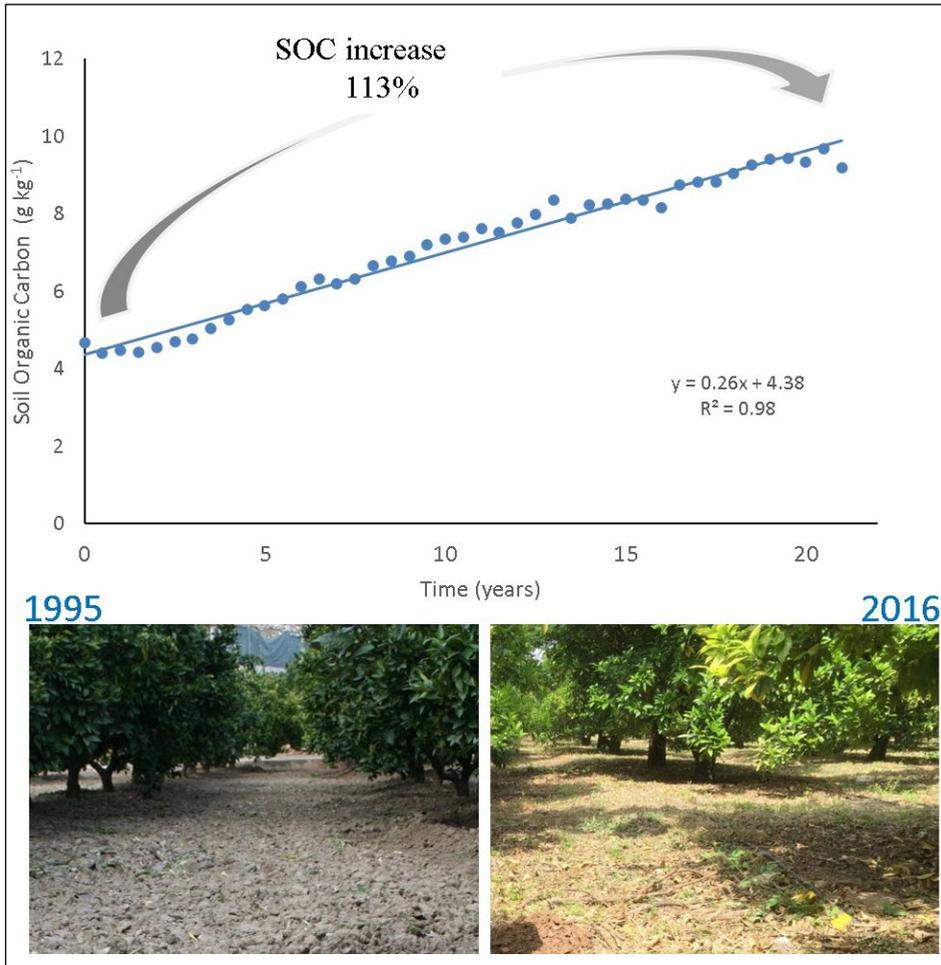


Figure 1. Soil organic carbon content (g kg^{-1}) during the long term experiment in 0-31 cm soil depth. Pictures of the citrus orchard in 1995 and 2016.

The effect of organic farming on SOC content over 21 years decreased with soil depth (Fig. 3). The increase of SOC was 126% in the 2-3cm soil depth, 51% in the 7-8 cm soil depth, and 53% at 17-18 cm soil depth. The SOC increase was not significantly different at 31 cm soil depth, although the SOC content slightly increased from $3.29 \pm 0.96 \text{ g kg}^{-1}$ to $3.66 \pm 2.02 \text{ g kg}^{-1}$ (Fig. 3).

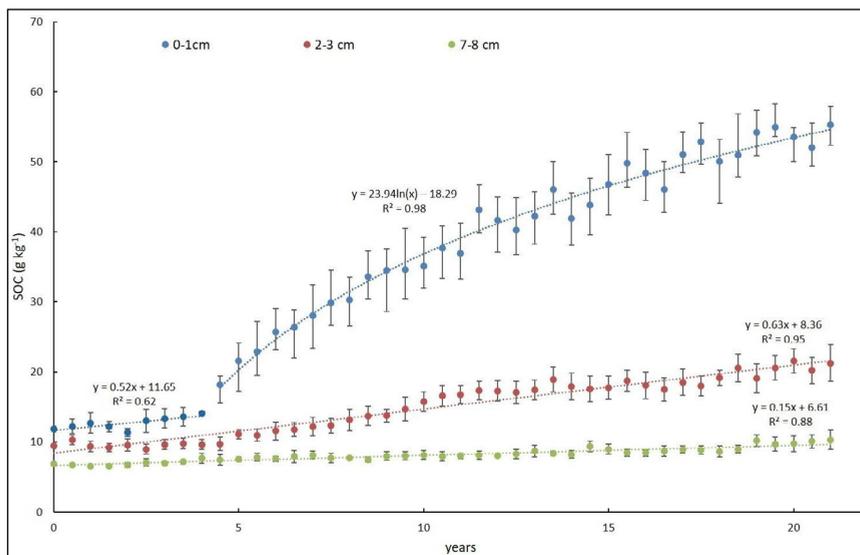


Figure 2. Soil organic carbon content in the top three soil layers (0-1cm; 2-3 cm and 7-8 cm) during 21 years of citrus organic farming. Bars indicate standard error (n=10).

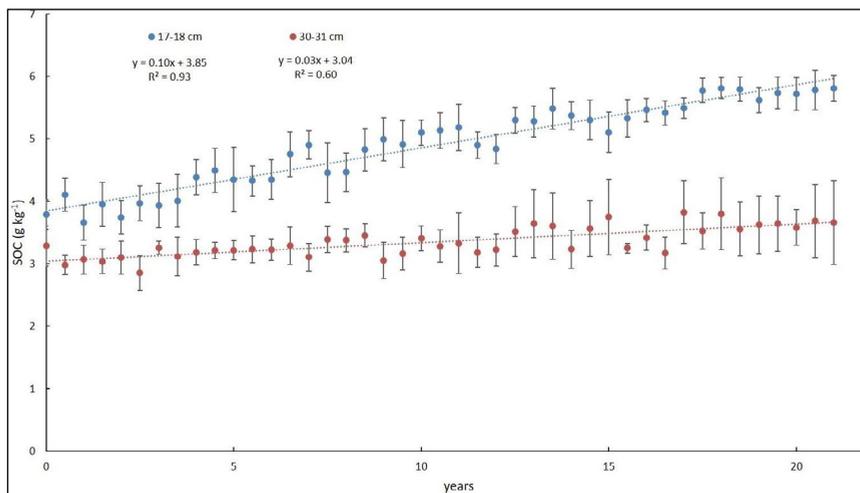


Figure 3. Soil organic carbon content in the deepest two soil layers (17-18cm and 30-31cm) during 21 years of citrus organic farming. Bars indicate standard error (n=10).

3.2. Effect of organic farming on soil bulk density

Organic farming had a significant effect on soil bulk density in all soil layers, except for 30-31 cm soil depth (Fig. 4). After 21 years, the bulk density values

decreased by 16 %, 17%, 12% and 12% in 0-1cm, 2-3cm, 7-8cm and 17-18cm soil depths, respectively. These findings were consistent with several studies which demonstrated that organic matter decreases bulk density, due to a decrease of the denser mineral fraction, and due to an increase of aggregation and soil pores (Khaleel *et al.*, 1981; Pagliai, 1988). However, the results of this study were in contrast with other long-term field experiments which found an increase in bulk density using alternative management due to no till. Several authors found that under no till management, soils had greater bulk density in comparison to conventional tillage, despite the fact that residues were left in the field (da Silva *et al.*, 2001; Kushwaha *et al.*, 2001). Our data showed an increase in the bulk density in the top layer in the first 5 years, during which time that the soil organic matter did not increase significantly (Fig. 3), and most likely the soil biota had not yet recovered. The soil in the top layer that was tilled for millennia is slightly compacted. This is also clearly observed in fields that are under no-tillage practice in combination with the use of herbicides (Di Prima *et al.*, 2018). Here the bulk density increased, causing much lower infiltration capacity and higher runoff and erosion (Keesstra *et al.*, 2016b). However, in the organically farmed site of our study, the soil was left untouched and fed with organic matter from the top. This is why the behaviour contrasts with tilled soils and has similar organic matter behaviour to forest soils (Adams, 1973; Ellert and Bettany, 1995; Périé and Ouimet, 2008).

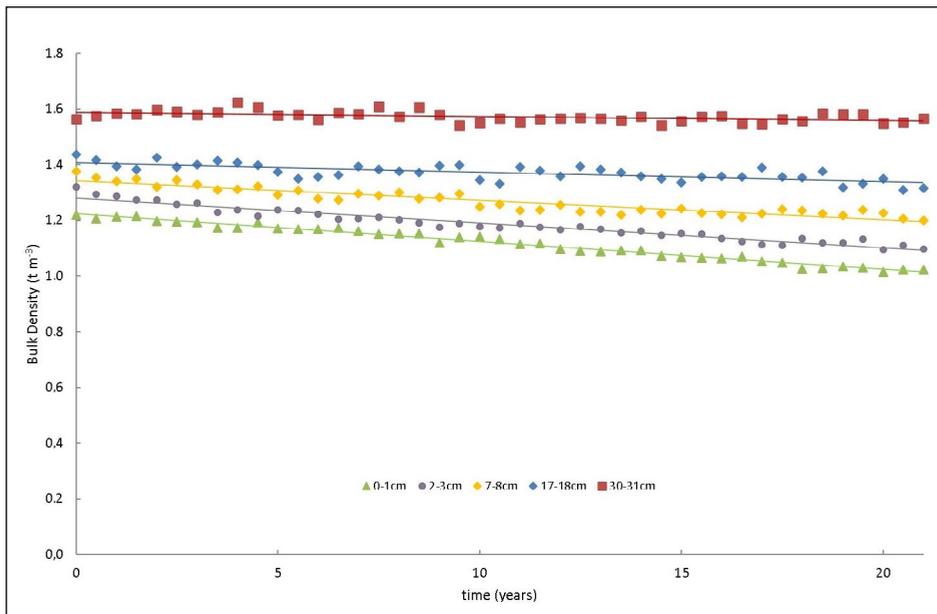


Figure 4. Evolution of soil bulk density in different soil layers.

3.3. Soil organic carbon stock and sequestration rate

Over the whole 21-year period, 16.5 Mg ha⁻¹ of organic carbon was sequestered into the soil, corresponding to a SOC sequestration rate of 0.78 Mg C ha⁻¹y⁻¹ (Fig. 5). The same C sequestration rates were found in Mediterranean environments after the conversion from conventional to alternative soil management using cover cropping residues: for instance, in a meta-analysis (16 studies) Vicente-Vicente *et al.* (2016) found average values of C sequestration of 0.78 Mg ha⁻¹y⁻¹ after the conversion of orchard from conventional to cover crop soil management. In a meta-analysis (74 studies), Gattinger *et al.* (2012) found, on average, a C gain of 0.45 ± 0.21 Mg C ha⁻¹ y⁻¹ for organic treatments in comparison to conventional management.

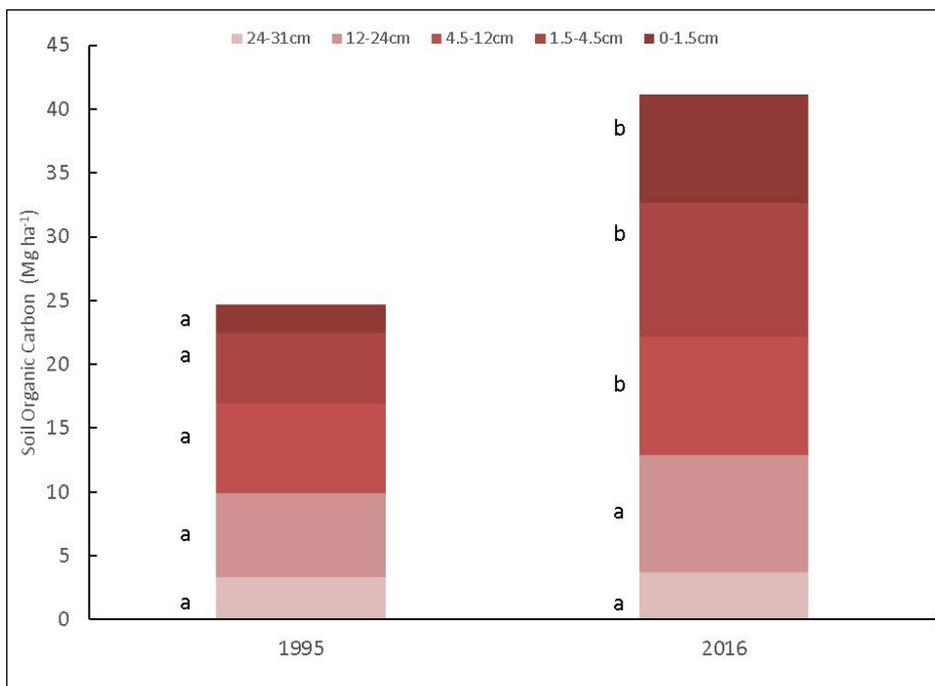


Figure 5. Soil organic carbon (Mg ha⁻¹) stock in different soil layers. The same letter for each soil layer indicates no significant difference in SOC stock between the two dates (1995 and 2016). The annual C sequestration rate did not significantly change during the 21 years of observation in this study, with values ranging from -1.10 Mg C ha⁻¹ y⁻¹ to 1.89 Mg C ha⁻¹ y⁻¹. This result was in contrast with other studies carried out in semiarid environments, where an asymptotic trend of SOC stock in relation to time or C input was found (Gattinger *et al.*, 2012; Novara *et al.*, 2016). The linear increase of SOC under organic citrus management indicates that SOC steady state has not been reached and that the whole soil practices (residue, no till, and weed biomass residue) are still effectively contributing to SOC restoration and with continued carbon sequestration after 21 years.

The introduction of organic farming in citrus plantations resulted in an increase in SOC content, thereby contributing to greenhouse gas mitigation. After

21 years, 61 Mg CO₂ ha⁻¹ was sequestered and converted to long-lived SOC pools. Since the increase in SOC began to be seen after 5 years since land management change, studies of soil C change in Mediterranean environments should be longer than five years.

3.4. The benefits of organic farming

The experimental research conducted at the L'Alcoleja study site demonstrates that organic farming increases soil organic matter content and can sequester carbon from the atmosphere. But there is more. The scientific literature shows that organic farming also contributes to healthy soils due to the lowering of the bulk density such as found here. Other researchers found that organic farming contributes to increasing floral and faunal diversity. Hole *et al.* (2005) found that there is a clear benefit when organic farming is applied, and this varies among taxa (Fuller *et al.*, 2005). This is also related to the improved natural fertility of the soil that allows for higher biodiversity, which leads to an improvement of the ecosystem services offered by the soil to human society (Winqvist *et al.*, 2012).

More than fauna and flora, organic farming also offers a more diverse landscape. The research of Smith *et al.* (2010) showed that organic farming contributes to landscape heterogeneity and this is related to the landscape complexity, as Norton *et al.* (2009) found that there is a clear threshold when organic farming substitutes non-organic farming. The impact of organic farming goes further when analysed from a holistic point of view. Pimentel *et al.* (2005) found that environmental, energetic and economic comparisons between organic and conventional farming systems show that organic farms are more sustainable. The impact of organic farming can also affect the quality of the products with higher nutritional quality, leading to better services to humankind (Worthington, 2001). The establishment of the organic farming must contribute to clean water, as all farming delivers nutrients to the soil and fluvial system (Pang and Letey, 2000; Schröder *et al.*, 2004). Organic farming has similar environmental impacts as land abandonment. From the water resources point of view, there is more water intercepted (catch crops, grass covers) and more water use by the plants such as Lana-Renault *et al.* (2018) and Zuecco *et al.* (2018) demonstrated at catchment scale, and Cerdà *et al.*, (2018c) at plot scale. The benefits of organic farming are similar to the use of restoration strategies, such as Hueso-González *et al.* (2017) found in fire-affected land with the use of compost and with the use of chipped pruned branches and straw mulches.

5. Conclusion

Organic farming in citrus plantations is a significant strategy for SOC restoration and climate change mitigation. Although sequestration of SOC is more difficult in a Mediterranean environment due to the climatic conditions, results of a 21-years experiment showed a significant SOC increase in the first 0-31 cm of soil. Most of the organic matter was accumulated in the surface, as no-tillage took place in the orchard. There was a constant increase in SOC with an average of 0.78 Mg C ha⁻¹ y⁻¹ that finally resulted in 61 t CO₂ ha⁻¹ sequestered over the research period. These findings provide a

quantitative result for C accounting studies; and are helpful to address future policies on soil management.

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