

Conventional tillage versus cover crops in relation to carbon fixation in Mediterranean olive cultivation

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Abstract

Background and Aims For croplands, controversy persists concerning the adequacy of the soil use and the management of environmental problems such as soil erosion and fertility in a context of climate change. In this study, we used the RothC model to evaluate the capacity of carbon fixation by the soil in a Mediterranean olive grove for two different scenarios: the land-use change from native vegetation (NV) to conventional tillage (T) in the olive grove, and for the change in soil management from conventional tillage to cover crop (CC).

Methods In three experimental olive groves in Andalusia (S Spain) two soil-management systems were sampled: T and CC. Areas of NV adjacent to the grove were also sampled as indicative of the initial state of the soil without olive trees. We measured the above-ground biomass production of the cover and the clay content, bulk density, and soil organic carbon (SOC) for 0–5, 5–15 and 15–30 cm depth.

Results The removal of NV to implement T resulted in a significantly loss of SOC that depended mainly on the relief of the terrain. However, the use of CC increased the SOC because of greater inputs (above- and belowground plant inputs) to the soil. The final concentration at each location was related to the carbon inputs and the clay content. The CC resulted in carbon storage during the first year of 4.02 ± 1.65 Mg C ha⁻¹, and a total carbon fixation by the soil of 5.91 ± 2.06 Mg C ha⁻¹.

Conclusion The use of cover crops in Mediterranean olive groves proved to be a suitable strategy to increase the carbon storage into the soil and then to decrease the CO₂ concentration in the atmosphere.

Keywords Soil organic carbon · Olive grove · Belowground carbon input · RothC model

Introduction

Olive groves in the Mediterranean basin cover some 9.5 million ha. In Spain it is one of the most important crops, accounting for 15 % of the total area cultivated in Andalusia (southern Iberian Peninsula). Conventional management of the olive grove uses a low tree density (c. 100 trees ha⁻¹), where the soil between trees is maintained vegetation free year round by continual soil tillage and more recently by the application of herbicides (Saavedra and Pastor 2002). Conventional tillage (T) involves a number of negative aspects

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such as water loss by evaporation (Pastor 2004), the destruction of the soil structure, loss of organic matter and nutrients (Balesdent et al. 2000; Paustian et al. 2000), and higher erosion rates (Francia et al. 2006; Martínez-Mena et al. 2008; Gómez et al. 2009b). Inadequate conventional soil-management practices in certain zones, together with the decline in the input of nutrients to the system, have strongly degraded the environment related to this sector (Beaufoy 2001).

In recent years, controversy has arisen over the suitability of the different management systems to solve problems of erosion and fertility in the olive grove. Live cover crops (CC) currently constitute one of the major directions in agro-ecological olive-grove cultivation. To protect the soil from degradation and erosion, to increase the organic-carbon content (SOC) and thereby improve its structure as well as fertility constitute the main goals of this type of management (Castro et al. 2008; Gómez et al. 2009b; Ramos et al. 2010). Usually, CC consists of Gramineae and/or Leguminosae cultivated in the zone between trees and maintained from autumn until spring to avoid the competition for water with the olive tree. These covers can be cereal crops or weeds, but nothing is removed as harvest, so that the soil is covered during the growing season and later the crop covers the soil surface with debris.

Today, carbon sequestration in agriculture is one of the most important subjects in Soil Science as a means of fixing or emitting carbon (C), depending on the parameters that determine the balance of net C inputs to the soil and net losses of C from the soil (Smith 2008). Many studies estimate rates of C sequestration associated with soil-management changes. However, Feller and Bernoux (2008) pointed out that the concept of soil C sequestration should not be restricted to a mere quantification of C storage, although all greenhouses gases need to be computed in C-CO₂ or CO₂ equivalents, considering as many emission sources and sinks as possible across the entire soil-plant system. Therefore, this concept should be used with caution, indicating in all cases the parameters used in calculating the C balance.

Most estimates for the potential C sequestration of agricultural activities for European soils range from about 0.3 to 0.8 Mg C ha⁻¹ year⁻¹, but some estimates fall outside this range (Smith 2008). Because of the climatic conditions of semiarid Mediterranean Spain, this area has a great potential for C sequestration

(Vleeshouwers and Verhagen 2002; Smith et al. 2005). In this area, several studies have reported SOC changes in agricultural soil management, but only a few have reported C sequestration data (Testi et al. 2008; Álvaro-Fuentes et al. 2009; Hernanz et al. 2009). Most of these studies, on cereal crops, have recorded increases in SOC content associated with a greater input of plant debris to the soil and the switch from tillage to non-tillage (NT). For example, Hernanz et al. (2002) registered 3.4 and 5.4 Mg C ha⁻¹ more (increases of 10 and 18 %) for the 0–30 cm profile after changing from T to NT. Ordóñez Fernández et al. (2007) found 18 Mg organic matter ha⁻¹ more (increase of 20 %) after 10 years of NT and residue management in the 0–50 cm soil profile. López-Fando et al. (2007), reported an increase after 2 years of NT by 3.96 Mg C ha⁻¹ compared to T (increase of 13 %) in the 0–30 cm layer. Recently, examining cereal/legume crop rotation, Hernanz et al. (2009) reported that, after 10 years, SOC in NT was 8.5 Mg C ha⁻¹ higher than for T (increase of 75 %) in the top layer (0–10 cm).

In the Spanish Mediterranean area, where a high proportion of land use involves olive groves, the C balance with the atmosphere needs to be characterized (Domingo et al. 2011), especially associated with changes in land use or soil management, and then estimate the real potential of soil in climate change. Despite the lack of information on C flow in the soil, the use of cover crops and the lack of tillage in olive groves is well known, since the input of plant remains from vegetable covers and the lower mineralization ratios significantly increase SOC (Castro et al. 2008; Martínez-Mena et al. 2008). However, C balance into the soil accounting total C inputs and outputs have not been yet characterised. Hernández et al. (2005), in a plot with mechanical mowing, registered 74 % SOC increases in a natural CC with respect to T, for the shallowest soil, while Gómez et al. (2009b) found that the use of CC controlled by herbicide doubled the SOC (0–10 cm) with respect to T after 7 years. In a cover formed by shredded olive-pruning debris and plant residues from the olive-fruit cleaning at the oil mill, Nieto et al. (2010) reported a SOC increase of up to 6- and 4-fold in comparison to T, 10 and 6 years after the soil-management change, respectively.

The SOC models help explain C dynamics in the soil-plant-atmosphere system and then predict possible alterations in the CO₂ exchange. In the Mediterranean

area, two main models, RothC (Coleman and Jenkinson 1996) and Century (Parton et al. 1994), have been applied for farmland and forest (Romanyà et al. 2000; Álvaro-Fuentes et al. 2009; Nieto et al. 2010; Martí-Roura et al. 2011). For this work, we chose the RothC model because it has been used at sites under diverse land uses and management systems worldwide (Smith et al. 1997; Jenkinson et al. 1999; Cerri et al. 2007; Gottschalk et al. 2010), including olive groves (Nieto et al. 2010), using a few widely available parameters. This model also makes it possible to determine the C fluxes in the soil profile according to the above-or belowground source of the inputs (Romanyà et al. 2000). This makes it an effective tool for assessing the effect of cover crops in C sequestration, differentiating inputs from the trees and from the plants of the cover. These previous studies have predicted greater C sequestration and therefore a fall in CO₂ emission to the atmosphere in soil management with non-tillage or increases in C inputs. But the CO₂ exchanges in the soil-atmosphere system related to changes in olive-grove soil management remains unclear, and information on the C balance and the role of cover

roots has not yet been reported. Consequently, the aim of this study was to evaluate the SOC changes in Mediterranean area associated to changes in soil use from native vegetation to conventional tillage olive grove, and the soil management change from conventional tillage to cover crop. In addition, the evaluation of C-fixation capacity by the soil under the cover crop is assessed using the RothC model.

Material and methods

Study area

Three study farms were selected in major olive-producing areas in Andalusia (S Spain): Granada (*Castillo*), Málaga (*La Torre*), and Córdoba (*Matallana*), as shown in Fig. 1. The climate is typically Mediterranean, with mild rainy winters and hot, dry summers. The average temperature, rainfall, and other characteristics of each farm are given in Table 1. The intense agriculture of the area has limited native vegetation to zones that, due to limiting factor such as rocky outcrops, cannot be used for cultivation. In

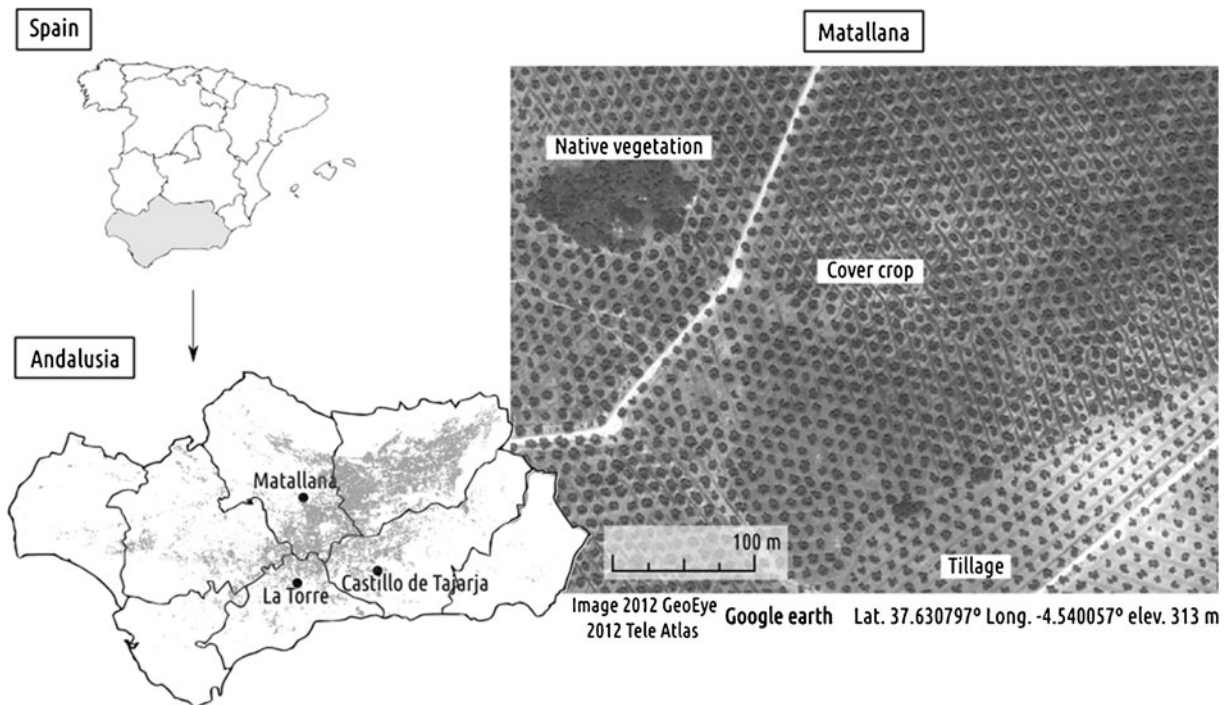


Fig. 1 Location of the study area and aerial photography of Matallana with the three sampling points: native vegetation and conventional tillage and cover crop olive grove

Table 1 Average annual mean air temperature, total annual precipitation, soil type (FAO 2006), soil texture, altitude and mean slope in the three locations

Location	Mean temperature (°C)	Precipitation (mm yr ⁻¹)	Soil type	Texture	Altitude (m a.s.l.)	Slope (%)
Castillo (37.12°N 3.88°W)	15.2	452	Vertic Calcisol	silty clay	720	10
Matallana (37.63°N 4.54°W)	16.0	577	Vertic Calcisol	clay/silty clay	310	<4
Torre (37.02°N 4.70°W)	17.1	454	Hypercalcic Calcisol	sandy clay loam	410	6

Meteorological station: Chimeneas-Castillo (37.18°N 3.78°W), Espejo-Castro del Río (38.51°N 4.76°W) and Bobadilla-Estación (37.45°N 4.80°W).

these patches, the natural vegetation is often a perennial, sclerophyllous woodland of Holm oak (*Quercus ilex* L.) typical of the Mediterranean basin.

Two different soil-management systems for olive groves were sampled in this work. The initial soil management was conventional tillage (T) to control weeds. In a different year for each location (Table 2), the soil management was changed to cover crop (CC), and weeds were left to grow each year. All practices were applied only to the open gaps between the trees, about 35 % of the total area of the grove. Beneath the trees in T and CC, weeds were eliminated with pre- and post-emergence herbicides, while dead leaves, dried fruit, and twigs were removed by raking or sweeping without breaking the surface crust. Both T and CC were sampled in neighbouring areas having the same soil characteristics. An example of sampling points is shown in Fig. 1 for Matallana. Areas of native vegetation (NV) adjacent to the crop were sampled to determine the state of the soil without olive trees. We assumed a steady state for T and NV. This assumption means that there is no change in the SOC year-a-year, so that the capacity of soil for C accumulation in each one is in equilibrium with C inputs (Ingram and Fernandes 2001). As pointed out by Freibauer et al.

(2004), increases in soil C are often greatest soon after a land-use or land-management change is implemented. As the soil reaches equilibrium, the rate of change decreases, so that after between 20 and 100 years a new equilibrium is reached. According to Sánchez-Salazar (1989), olive expansion occurred in the eighteenth century, so we considered that this management has been used for a long enough time to be considered in equilibrium. In addition, Almagro et al. (2010) assumed that conventional olive groves reach a steady state after 50 years of the same agricultural management. From 100 soil profiles under conventional-tillage olive groves located in the study area, Nieto et al. (2010) indicated SOC equilibrium after 30 years of T. The soil-management systems and locations are summarized in Table 2.

Sampling and analysis

In 2007 at Castillo and 2008 at Matallana and La Torre, random soil samples were taken in the olive grove between trees and in the patches of NV, after removing the fresh plant debris on the soil surface. Pits measuring 50×100×50 cm were dug and the samples were taken on one side of the pit. The soil samples

Table 2 Characteristics of soil use and management evaluated at the three locations

Soil use and management		Castillo	Matallana	La Torre
Native vegetation	Time	Equilibrium	Equilibrium	Equilibrium
	Description	Perennial, sclerophyllous Holm oak forest		
Tillage	Time	Equilibrium	Equilibrium	Equilibrium
	Description	Two-three disc harrow and cultivator passes (0.20 m) twice a year to control weeds		
Cover crop	Time	1993–2007	1996–2008	2006–2008
	Description	Cover crop of weeds controlled by herbicides in March. Debris left on the soil surface with non-tillage practices		

Equilibrium means no changes in land use or management in at least the last 50 years.

were collected at depths of 0–5, 5–15, and 15–30 cm. The bulk density (BD) was determined from the pits following the method of Blake and Hartge (1986), using a cylinder of 5 cm high, and correcting the total volume according to the percentage of gravel, similar to that proposed by Throop et al. (2012).

$$BD = \frac{Wc - Wg}{Vc} \quad (1)$$

where Wc is the dry weight of the soil in each cylinder (g), Wg is the weight of gravel (> 2 mm) (g) and Vc is the volume of the cylinder (cm³). Then, SOC content (Mg Cha⁻¹) was calculated by Eq. 2:

$$SOC [Mg C ha^{-1}] = OC \times BD \times d \quad (2)$$

where OC is the soil organic C concentration (%) and d is the soil depth (cm)

Three replicate plots per area (Castillo, Matallana and La Torre) and soil use and management type (T, CC and NV) were sampled. All the soil samples were air-dried, ground, and sieved through a 2-mm sieve. The soil-particle distribution was analysed using the Robinson pipette method (Soil Conservation Service 1972). A subsample of fine earth of each sample was finely ground in a agatha mortar to analyse total organic C by wet oxidation with dichromate following the method of Tyurin (1951). The aboveground biomass of the cover crop was measured by throwing a quadrat of 30×30 cm randomly into the grove lane. The plant material was placed in paper bags, then oven dried at 60 °C and weighed. The C content was determined by dry combustion with a LECO-carbon-analyzer TruSpec (LECO Corporation, St. Joseph, MI, USA).

RothC model

A detailed description of the model is given by Coleman and Jenkinson (1996). In brief, the RothC model separates the SOC into four active compartments and a small amount of inert organic matter (IOM). Plant residues reintroduced to the soil are divided into decomposable plant materials (DPM) and resistant plant materials (RPM), both undergoing decomposition to produce microbial biomass (BIO), humified organic matter (HUM) and CO₂ (lost from the system). The clay content, soil moisture, temperature, and plant cover of the

soil determines the proportions that go from one compartment to other or to CO₂.

The climate input parameters include monthly average air temperature, monthly precipitation and monthly open-pan evaporation. Other input parameters are soil-clay content, monthly carbon input from plant residues or farmyard manure, and monthly information on soil cover, whether the soil is bare or covered by plants. The decomposability of the incoming plant material is estimate by the DPM/RPM ratio, using a ratio of 1.44 for most agricultural and improved grassland, and 0.67 for scrubland and non-improved grassland (Coleman and Jenkinson 1996). The C supply from the live CC was distributed primarily in the months of February, March, and April. IOM in RothC is defined as a small fraction of soil organic matter that is stable and biologically inert, and has a high radiocarbon age (Falloon et al. 1998). It is a device to allow the model to represent short-term changes in SOM brought about by changes in land management and at the same time to account for the great radiocarbon ages measured in surface soils collected before thermonuclear tests (i.e. prior to 1960). Since these data are rare and expensive, Falloon et al. (1998) developed a regression equation to estimate the size of the IOM pool from SOC which was used in this work:

$$IOM = 0.049 \times SOC^{1.139} \quad (3)$$

According to the model, the soil cover affects the decomposition of the organic matter, decreasing in soils with actively growing vegetation. Previous works that have used this model in agricultural soils have done so primarily for crops in which the fallow soil is equivalent to the total elimination of vegetation (Smith et al. 1997). However, in a tree crop, such as the olive grove, the vegetation is not eliminated after the harvest but rather the tree continues to grow throughout the year. Furthermore, the olive tree has a robust fasciculate root system and concentrates greater density of fine roots in the most superficial zone of the soil, frequently in the first meter depth (Fernández and Moreno 1999). For these reasons, the entire surface of the olive grove was considered to be covered year round, since although there was no vegetable matter supplied to the surface, or it was very scant, C was continually supplied by the roots.

It bears mentioning that the soil-cover parameter combines two characteristics that in the olive grove are separate: tillage and the presence of roots in depth. If

the speed of decomposition of the organic matter is controlled by this parameter, it would be necessary to add another factor or an intermediate value that would include not only the C supply by the roots but also the effect of tillage. In the case of tree crops, the mineralization rate in the uppermost 30 cm would be controlled by the presence of roots over the year (which would be broken after one pass of tillage but which are immediate responses by the olive grove) together with the effect of turning over the soil surface, which increases mineralization of the organic matter.

The RothC model was used in different ways. Firstly, it was performed in equilibrium for the NV and the T olive grove, and C inputs were calculated running the model in reverse mode by fitting to the measured data. Then it was performed for two scenarios: i) for the soil-use change from the NV to the T olive grove in the uppermost 30 cm (0–30 cm layer), and ii) for the soil-management change from the T to the CC olive grove in three intervals based on the depth of sampling: 0–5, 0–15, and 0–30 cm. The simulation was carried out by fitting the modelled and measured data for SOC according to the year of cover crop sown (Table 2). For this scenario, IOM was calculated from the T soils in equilibrium.

The calculated total C input for the 0–5, 0–15, and 0–30 layers of CC indicated the amount of C input that came from above and belowground (root production) for both the olive trees and the weeds. The first soil layer sampled coincided with the limit of the weeds roots (5 cm). This limit was established during the sampling. Similarly, olive roots were not observed in this layer. Belowground C input only from the CC was calculated for the 0–5 cm layer, as indicated below:

$$\begin{aligned} \text{Cover crop}_{\text{belowground}} &= \text{Total C input} - \text{Cover crop}_{\text{aboveground}} \\ &+ \text{Olive tree}_{\text{aboveground}} \end{aligned} \quad (4)$$

According to Nieto (2011) the aboveground C input from the olive tree (Eq. 4) to the soil is $0.32 \pm 0.11 \text{ Mg C ha}^{-1} \text{ year}^{-1}$. This value was calculated from two fields in NT with bare soil located in the same area as the present work.

For the 0–15 and 0–30 layer,

$$\begin{aligned} \text{Olive tree}_{\text{belowground}} &= \text{Total C input} \\ &- \text{Total C input in the upper layer} \end{aligned} \quad (5)$$

The turnover time was calculated as the total organic carbon content except IOM divided by the annual C input into the soil (Jenkinson and Rayner 1977). Finally, the model was run for the first 100 years after changing the soil management in the olive grove to check whether it achieved a new steady state.

Carbon balance

In this work, the C balance was calculated in two different ways according to Feller and Bernoux (2008). Firstly, SOC storage was calculated as the difference in the content of organic C in T and the cover system (CC). Secondly, SOC fixation was calculated as the difference between soil-C inputs and the outputs because of organic-matter mineralization (heterotrophic respiration modelled by RothC) for the first year after the change in management.

Statistical analysis

The statistical analysis was used to identify possible differences between locations. These differences were assessed by one-way analysis of variance (ANOVA) at a confidence level of 95 %. The Tukey-HSD test was performed for *post hoc* comparisons between levels within each considered factor. Prior to analyses, Bartlett and Shapiro-Wilk tests were applied to check homoscedasticity and normality, respectively, to ensure that assumptions of the model were met. In case of violation of the Bartlett test, the nonparametric test of Kruskal-Wallis was used. To compare the difference between measured and modelled data was used the root mean square error (RMSE) and the mean difference between measurements and simulation (Smith et al. 1997). All data were analysed using SPSS v.15.0 and Statistix 8.0.

Results

Carbon input in native vegetation and tilled olive grove

The clay content, SOC, and C input modelled by RothC for the NV in the three locations are shown in Table 3. Despite the variations, SOC did not significantly differ

Table 3 Clay content, measured soil organic carbon (SOC), inert organic matter (IOM), modelled carbon input and turnover time for the patches of native vegetation (0–30 cm)

Location	Clay (%)	Measured SOC (Mg Cha ⁻¹)	IOM (Mg Cha ⁻¹)	Modelled C input (Mg Cha ⁻¹ year ⁻¹)	Turnover time (yr)
Castillo	47a	148.0±40.0	14.5	4.42±1.17	30a
Matallana	41a	82.8±5.3	7.5	3.14±0.19	24ab
Torre	26b	104.2±41.3	9.7	4.86±1.96	20b
Mean		111.6±40.8		4.14±1.38	25±5
ANOVA (F)	21.7	2.99		1.37	
Sig. (<i>p</i>)	0.002	0.126		0.324	<0.001

Different letters indicate significant differences between locations according to the Tukey's test ($p < 0.05$).

between locations because of the high standard deviation. However, the clay content was significantly lower in La Torre. The modelled C input was related to the clay content and SOC, with the lowest value in Castillo (high clay and SOC) and the highest in La Torre (lower clay but similar SOC than Castillo). In Matallana, the lower C inputs coincided with the lower SOC concentration. The turnover time was higher than 20 years in all cases, with a maximum in the soils containing more SOC (Table 3).

The results for the T olive grove are presented in Table 4. The clay values resemble those registered in NV for La Torre and Matallana but not Castillo, which showed a 15 % decline ($p = 0.06$). The SOC was significantly lower at this location, also, related to the other fields. On the other hand, the soil with a higher clay content (Matallana) registered more SOC than did the other locations. In general, the C input to the soil was related mainly to the SOC concentration, with minimum values in Castillo and maximum in Matallana. As in NV (Table 3), the turnover time was high

at all locations, (average 24±5 year). As expected, IOM decreased significantly with respect NV (minimum of 1.0 Mg C ha⁻¹ year⁻¹ in Castillo).

Land-use change from native vegetation to tilled olive grove

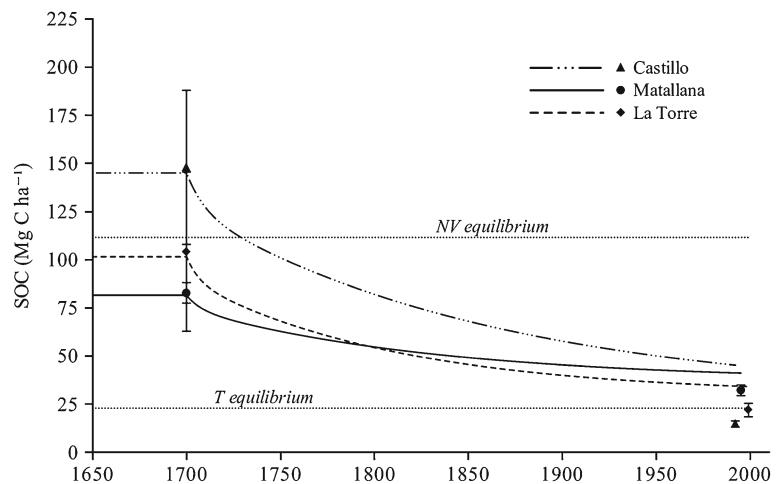
Based on modelled C inputs for the NV and T, the RothC model was used to simulate the land-use change. The results were checked with the measured SOC at each location. In this scenario, C input in NV and T was the average of the study areas, i.e. 4.14 and 0.92 Mg C ha⁻¹ year⁻¹, respectively. IOM was calculated at the beginning of the process from the SOC content in NV. According to the model, this value is constant over time because the IOM is physically protected from decomposition. The results of this simulation are shown in Fig. 2, where lines represent the evolution of SOC for each farm from native vegetation in equilibrium. According to Sánchez-Salazar (1989),

Table 4 Clay content, measured soil organic carbon (SOC), inert organic matter (IOM), modelled carbon input, and turnover time for the tilled olive grove (0–30 cm)

Location	Clay (%)	Measured SOC (Mg Cha ⁻¹)	IOM (Mg Cha ⁻¹)	Modelled C input (Mg Cha ⁻¹ year ⁻¹)	Turnover time (yr)
Castillo	32ab	14.7±1.6a	1.0	0.46±0.04a	29a
Matallana	43a	32.2±2.8b	2.6	1.22±0.10b	24ab
Torre	23b	21.9±3.5c	1.6	1.06±0.16b	19b
Mean		22.9±8.0		0.92±0.36	24±5
ANOVA (F)	11.5	30.5		39.6	
Sig. (<i>p</i>)	0.009	0.001		<0.001	<0.001

Different letters indicate significant differences between locations according to the Tukey's test ($p < 0.05$).

Fig. 2 Soil organic carbon (SOC) content measured (points) and modelled by RothC (lines) for the land-use change from native vegetation to tilled olive grove at each location (0–30 cm). The average SOC measured in each use is shown by horizontal dashed lines



olive expansion occurred in the eighteenth century, so the NV values represented the initial state. The values measured in the field in both uses (NV and T) are represented by points. The horizontal dashed lines indicate the average value in each. Also Table 5 summarizes the principal data of this simulation.

After changing the land use and therefore the associated carbon input, the SOC concentration decreased sharply during the first years, reaching a new equilibrium at the end of the simulation (Fig. 2). As shown, the model was fitted to the patches of NV, giving good estimates, with a RMSE lower than 20 % and values close to the average and within the error of each location, except that of Matallana (Table 5). However, the SOC measured in the tillage olive groves was lower than simulated, especially in Castillo (RMSE=183.7 %). In fact, the variation between average SOC in T soils and the modelled value by RothC was significantly different

in all locations, with a SOC gap ranging between 9.4 and 46.6 Mg C ha⁻¹ for the three locations. The RMSE was higher than for NV in the three fields. Figure 2 shows that the fall in SOC content was smaller in Matallana, which had a higher clay content. In La Torre, with less clay, the decline was faster, resulting in lower modelled SOC at the end of the simulation. These results were also found in the measured data.

Soil-management change from conventional tillage to cover crop

The change of soil management significantly increased the SOC content at all locations, with the highest values at Castillo (Table 6). The difference between T and CC was more important in soils with more degraded conditions in T and a longer time of cover use (Table 2).

Table 5 Soil organic carbon (SOC) content measured and modelled by RothC for the change in land use from native vegetation (NV) to tilled olive grove at each location (0–

30 cm). Soil-organic-carbon gap was calculated as the mean difference between modelled and measured data

Location		Measured SOC (Mg Cha ⁻¹)	IOM (Mg Cha ⁻¹)	Modelled SOC (Mg Cha ⁻¹)	SOC gap (Mg Cha ⁻¹)	RMSE (%)	Sig. (<i>p</i>)
Castillo	NV	148.0±40.0	14.5	136.5±4.7		12.1	0.648
	T	14.7±1.6	14.5	61.3±4.3	46.6±4.6	183.7	<0.001
Matallana	NV	82.8±5.3	7.5	104.8±1.5		15.5	0.002
	T	32.2±2.8	7.5	41.6±0.7	9.4±2.9	17.1	0.005
Torre	NV	104.2±41.3	9.7	88.5±4.0		19.2	0.553
	T	21.9±3.5	9.7	35.1±4.3	13.2±5.5	36.9	0.015

RMSE: root mean square error; *p*-values in bold indicate statistically significant differences between measured and modelled SOC, with *p*<0.05.

Table 6 Measured aboveground carbon input for the cover crop and total modelled for the a) 0–5 cm, b) 0–15 cm, and c) 0–30 cm layers. Belowground carbon inputs were calculated as the difference between total and aboveground input

Location	Carbon inputs to the soil (Mg Cha ⁻¹ year ⁻¹)				Measured SOC (Mg ha ⁻¹)	Clay (%)	
	Aboveground		Belowground				Total
	Cover crop	Olive tree	Cover crop	Olive tree			
a. Measured aboveground carbon input for the cover crop and total modelled for the a) 0–5 cm layer. Belowground carbon inputs were calculated as the difference between total and aboveground input.							
Castillo	1.19±0.48	0.32±0.11	2.86±0.57a	0	4.37±0.57	24.3±3.0	45
Matallana	1.74±0.72	0.32±0.11	0.98±0.64ab	0	2.67±0.78	16.5±3.4	52
La Torre	2.01±1.28	0.32±0.11	0.83±0.78b	0	3.16±0.78	7.7±1.0	25
Mean	1.69±0.9		1.63±1.17		3.40±0.98		
Sig. (<i>p</i>)	0.099		0.028		0.070		
b. Measured aboveground carbon inputs for the cover crop and total modelled for the b) 0–15 cm layer. Belowground carbon inputs were calculated as the difference between total and aboveground input.							
Castillo	1.19±0.48	0.32±0.11	2.86±0.57a	2.39±0.42	6.76±0.69	41.2±3.6	46
Matallana	1.74±0.72	0.32±0.11	0.98±0.64ab	1.21±0.19	3.88±0.78	30.5±3.4	49
La Torre	2.01±1.28	0.32±0.11	0.83±0.78b	3.03±1.25	6.18±1.97	19.1±2.6	24
Mean	1.69±0.9		1.63±1.17	2.21±1.04	5.61±1.72		
Sig. (<i>p</i>)	0.099		0.028	0.069	0.072		
c. Measured aboveground carbon inputs for the cover crop and total modelled for the c) 0–30 cm layer. Belowground carbon inputs were calculated as the difference between total and aboveground input.							
Castillo	1.19±0.48	0.32±0.11	2.86±0.57a	5.03±0.73	9.39±1.12	59.9±5.8	46
Matallana	1.74±0.72	0.32±0.11	0.98±0.64ab	2.84±0.92	5.51±0.91	49.4±4.0	48
La Torre	2.01±1.28	0.32±0.11	0.83±0.78b	5.73±1.77	8.88±2.42	33.6±2.3	24
Mean	1.69±0.9		1.63±1.17	4.53±1.68	7.93±2.31		
Sig. (<i>p</i>)	0.099		0.028	0.064	0.050		

Different letters indicate significant differences between locations according to the Kruskal-Wallis non-parametric test ($p < 0.05$).

For the new scenario, RothC was run in reverse mode to calculate the above- and belowground C inputs to the soil at each location. Table 6 shows the carbon inputs to the soil from the tree and the cover crop for the 0–5 (Table 6a), 0–15 (Table 6b) and 0–30 (Table 6c) layer. In the 0–5 cm layer, it was assumed that there were no olive-tree roots so that the total C input in this layer would come from the CC (above and belowground plant parts) and from the fallen leaves, twigs, or fruits from the olive tree. In general, the use of a cover system increased the C input to the soil by the plants of the CC and the olive trees from both above- and belowground sources. The lowest total C input was registered in Matallana, which presented a higher clay content and an intermediate SOC value. In the bulk profile (30 cm), plants of the CC were responsible for 30–50 % of the total C added to the soil in all locations, reaching 70 % in the shallowest 15 cm of Matallana. From the total C

input of the plants of the CC, approximately 55 % came from aboveground biomass, the belowground contribution being lower. The effect of the olive-tree roots on the C input was more important from the 15 cm depth. Among sites, significant differences were registered only in the C contribution by the cover roots, which was related to the variability in the development of this cover.

Carbon balance

The C fluxes derived from the soil management are shown in Table 7. The emission values belong to the equilibrium state of T and to the first year of CC. The CO₂ emitted as a result of heterotrophic respiration (calculated from RothC model) rose significantly ($p < 0.05$) with the increasing C inputs in CC with respect to the T. The lowest values were registered in the T soil to

Table 7 CO₂ flow in the soil (Mg CO₂ ha⁻¹ year⁻¹) and soil organic carbon (SOC) for conventional tillage (T) at the beginning (t=0) and after the first year (t=1) of soil-management change to cover crop (CC). SOC storage is calculated as the

difference in the concentration of SOC in T and the cover system, and SOC fixation is calculated as the difference between soil-carbon input and the output

Location	CO ₂ flow (Mg CO ₂ ha ⁻¹ year ⁻¹)		SOC (Mg C ha ⁻¹)	SOC storage (Mg C ha ⁻¹ year ⁻¹)	SOC fixation
	Biomass input	Soil heterotrophic respiration			
Castillo					
T t=0	1.70±0.14	-0.46±0.04	14.7±1.6	5.35±0.54	7.63±0.99
CC t=1	34.47±4.11	-5.25±0.45	20.1±1.4		
Matallana					
T t=0	4.49±0.38	-1.22±0.10	32.2±2.8	2.18±0.48	3.63±0.75
CC t=1	20.21±3.35	-3.63±0.51	34.4±2.9		
Torre					
T t=0	3.89±0.57	-1.06±0.16	21.9±3.5	4.53±1.26	6.48±2.38
CC t=1	32.60±8.88	-6.00±0.88	26.4±2.3		
				4.02±1.65	5.91±2.06

The sign (-) means emission.

Castillo, the field with the least C input. The contribution of plant debris to the soil-CO₂ flux changed depending on management, with 27 % in T and between 10 and 20 % in the soils with CC.

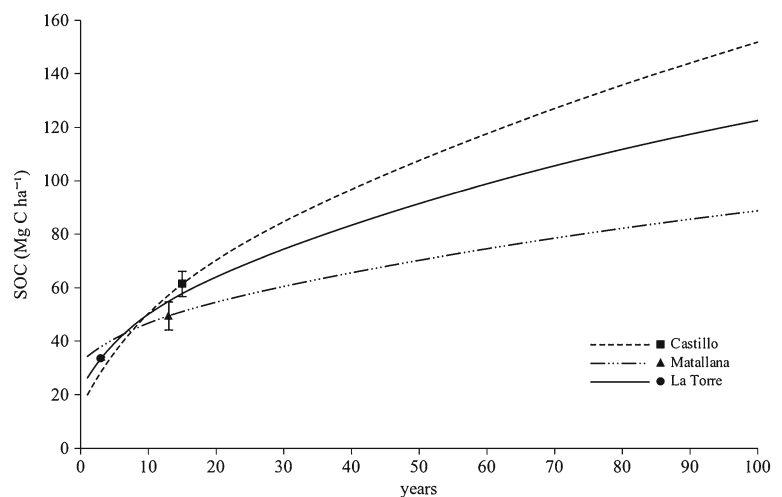
The addition of the biomass to the soil boosted the concentration of SOC and total C fixation by the soil (Table 7). The reported differences between locations depended mainly on the amount of biomass provided in each case. The greatest difference between T and CC was registered in Castillo and La Torre. In Matallana, the final SOC was slightly higher in CC than in T for the first year. The average C fixation was close to 6 Mg C ha⁻¹ year⁻¹. After a 100-year simulation by

the model, this location registered the lower SOC content too because of the lower rate of C fixation per year (Fig. 3).

Discussion

The SOC content depends mainly on the land use and/or soil management, which determines the total C input to the soil. This, together with the soil characteristics, determined the C balance in each case. As expected, the land use that registered the highest C input was NV, with values similar to those reported by

Fig. 3 Soil organic carbon (SOC) content modelled by RothC for the first 100 years of cover crop implementation (0–30 cm)



other authors for the Mediterranean area (Rosich et al. 1989; Ibáñez et al. 1999). According to these authors, the supply in the form of leaf litter in Mediterranean Holm oak forests ranges from 1.7 to 2.9 Mg C ha⁻¹ year⁻¹, with mean values of 2.32 Mg C ha⁻¹ year⁻¹. In depth, the C input from dead fine roots of this forest has been estimated at 1.66 Mg C ha⁻¹ year⁻¹ (Canadell et al. 1999). The sum of these values fall within the range estimated by the RothC model for the patches of native vegetation studied in the present work (3.98±0.39 as opposed to 4.14±1.38 Mg C ha⁻¹ year⁻¹). In the olive grove, the elimination of the NV significantly reduced the C inputs to the soil due to the low density of the planting scheme and to the scant use of plant remains produced by the crop in conventional management (Beaufoy 2001). Nieto et al. (2010) also indicated a descent in the C input associated with land-use change, estimating its value for conventionally tilled olive groves at 1.2 Mg C ha⁻¹ year⁻¹ (from one hundred soil profiles).

The clay content is another of the parameters which significantly affected the C content that can be stored in the soil. Some authors such as Hassink (1997) indicated that although the C input to the soil and accumulation had a direct relation, the presence of fine particles such as clay causes lower mineralization of the SOC and subsequent release in the form of CO₂. Thus this, clayey soils need less input from plant debris to reach the same SOC values as sandy soils. According to the RothC, the presence of clay in the soil influences the CO₂/(BIO+HUM) relation. That, the variations in the clay content of between 0 and 30 % prompt greater changes in the C input than do variations of an equal range from 30 % on (Coleman and Jenkinson 1996).

In the present work, the relation between clay content, C input and SOC was observed in the patches of NV from La Torre and Castillo (Table 3). According to our data, for similar total C input to the soil, the final SOC content was lower for less content in fine particle size (26 % clay in La Torre) than for clayey soils (47 % clay in Castillo). These data suggest the physical protection exerted by the fine soil particles on SOC mineralization. In T, the clay values were similar to those recorded in the NV for La Torre and Matalana but not for Castillo, where concentration decreased from 47 % in NV to 32 % in T. This result could be related to an increase in erosion as a consequence of the reduced soil cover, which affected the

loss of fine particles (Caravaca et al. 1999; Francia et al. 2006). In this management system, the variations registered among locations in the input modelled may have been conditioned by the parameters that affect the SOC content such as the erosion intensity or weed density.

In this sense, the lowest C levels were recorded in the T olive grove because of three events that may occur in a parallel and complementary form. First, a decline in the input of plant remains due to the low amount of crop debris that was spread. In olive groves managed in a conventional way, the biomass output were greater than the input, since together with the burning of the pruning remains, the fruit harvest extracted other debris that were also removed from the system. Furthermore, the T of the lanes and the use of herbicide under the canopies controlled the weed germination, diminishing the supply of plant remains. Second, the T favoured the mineralization of the organic material, affecting a number of physical and chemical conditions (moisture, temperature, aeration, nutrient availability, physical accessibility of the organic matter by microorganisms and enzymes). Thus, T physically altered the uppermost soil layers, destroying its structure and thus resulting in a greater C loss (Balesdent et al. 2000; Paustian et al. 2000). Third, the breaking up of aggregates has also been related to increased erosion rates (Hernández et al. 2005; Gómez et al. 2009a). In the present work, gullies and channels left by water as well as tree roots above the soil surface indicated strong runoff, especially visible in Castillo, where the slope was steeper (Table 1).

Erosion in the tilled olive groves has been amply studied. Thus, in tilled groves situated on slopes of 30 %, Francia et al. (2006) reported erosion rates of between 1.0 and 10.4 Mg ha⁻¹ year⁻¹, while Gómez et al. (2009b) measured losses of 2.9 Mg of soil ha⁻¹ year⁻¹ in groves with T. In terms of SOC, Boix-Fayos et al. (2009) indicated that the C loss by erosion after a land-use change varied between 2 and 78 % of the total stored in the uppermost 5 cm of the soil (mean of 0.15 % per year), with ratios ranging from 0.008 to 0.2 Mg C ha⁻¹ year⁻¹. Martínez-Mena et al. (2008) recorded SOC losses of 0.05 Mg C ha⁻¹ after 15 months in an olive grove under T, whereas in experiments by Gómez et al. (2009a), accumulations reached 0.2 Mg C ha⁻¹ year⁻¹. In agreement with these results, the quantity of C lost to soil erosion in the

study period could range from 12 to 60 Mg C ha⁻¹. The results of this work (mean 23.1±18.1 Mg C ha⁻¹ year⁻¹) fall within this range. The difference between the three geographic positions studied coincide with the risk of losses associated with their relief. Thus the highest values were found on the sites with the most abrupt topography and with the most degraded soil, as in the case of Castillo. The lowest values correspond to Matallana and La Torre, which had flat relief.

The discrepancy between the results simulated and the real ones measured for T (Table 5) indicated that this model does not correctly fit the changes in land use in the Mediterranean area, presumably due to the strong effect of erosion on the SOC concentration. Gottschalk et al. (2010) also indicated losses in SOC attributable to the erosion provoked by a land-use change that was not detected by the RothC model. These authors noted that the losses of SOC during continuous cultivation of soils previously uncultivated could not be simulated with precision because RothC fails to include an explicit description of the processes of physical protection of the soil. In this case, where a C loss occurred in association with erosive processes, it would be necessary to include in the model a parameter of the erosion rate that would control the decline in the SOC concentration and would enable the IOM value to be corrected over time, since it is resistant to mineralization but not to washing out. In relation to these results, Martínez-Mena et al. (2008) suggested that the main C pool mobilized by erosion is the most stable form (associated with the mineral fraction) while the effect of soil management preferentially affects the most labile fraction.

The C losses and in general the degradation of olive-grove soils have led to the development of management systems that protect the soil, such as CC. In the present work, the installation of a CC increased the SOC content in the uppermost 30 cm at all the study sites. This increase depended, as discussed above, on the annual input of C and the clay content. Figure 3 reflects that, for the same clay content, SOC is higher after 100 years due to greater C inputs (see Castillo and Matallana). Likewise, low clay content but high C input (La Torre) registered intermediate values. Other authors have found increased SOC in olive groves of the Mediterranean area with CC: Gómez et al. (2009b) indicated that the covers eliminated by herbicide doubled the SOC content over T plots. Álvarez et al.

(2007) registered maximum increases of 7 % in organically managed olive groves with pasturing, while Hernández et al. (2005) found rises of some 50 % on leaving the natural plant cover that had been eliminated by T. In almonds in the Mediterranean area, Ramos et al. (2010) documented increases of 66 and 56 % for oat and oat-vetch cover, respectively, in comparison to T.

The variations in SOC after a change in soil management were related not only to the increase in the biomass inputs by the plants of the CC (above- and belowground biomass) but also to lower losses. In general, the C supply by the plants of the CC represented 59 % of the total modelled C input in the uppermost 15 cm of soil (Table 6), and diminished on considering the top 30 cm of the profile, where the influence of the olive tree took on a predominant role (more than 50 % of the total C input). These results support the methodological hypothesis of the present work that, according to current modelling parameters of RothC, to simulate a soil of the olive grove, it should be considered that the vegetation in the grove is growing year round. In addition, the management systems with CC diminish the SOC losses of the soil on reducing the impact of T, primarily erosion and mineralization of the organic matter (Smith 2008). In Mediterranean olive groves, the lower effects of erosion and mineralization in CC have been previously documented (Francia et al. 2006; Gómez et al. 2009a).

The planting of a CC means a removal of atmospheric CO₂ by photosynthesis and its fixation in plant tissues. The decomposition of these remains gave rise to the greater heterotrophic respiration of the soil in CC as opposed to T due to the greater presence of organic remains. However, these plots registered the highest SOC contents, indicating a net gain (Table 7). The relationship between the C input and soil respiration have been mentioned by several authors (Bhogal et al. 2009; Gavrichkova et al. 2010), and this is based on an increase in organic matter, improved conditions for microorganism development, and therefore greater emission of the products resulting from the mineralization.

In olive groves, values have not been reported for heterotrophic respiration on the soil, although measurements have been made of the total flow of CO₂. In relation to the total emission of CO₂ from the soil, Almagro et al. (2010) registered a mean value of 4.27±0.30 Mg C ha⁻¹ year⁻¹ (c. 15.63 Mg CO₂ ha⁻¹ year⁻¹) in a rainfed olive grove in the province of

Murcia. Testi et al. (2008) measured soil respiration of $0.06 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (c. $18.92 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$) in an intensive olive grove of 408 trees ha^{-1} with bare soil. The results found in this work indicate the low weight of the heterotrophic respiration in the soils with low SOC contents and poor supplies of organic remains (typical of tillage), and therefore the greater influence of the roots of the olive trees or of the weeds in the CO_2 emissions of these systems. In cereal crops, which are similar to a Gramineae cover like the one used in the present work, Paustian et al. (2000) registered CO_2 emission by respiration at between 1.58 and $2.46 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ (c. 5.80 and $9.03 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$) in a barley crop and a rotation pasture in Colorado (USA), respectively, the values being similar to those found in the present work.

The use of various methods to estimate the soil-C sequestration reported in the literature makes the comparison of the data particularly difficult. In some works (e.g. West and Post 2002; West and Six 2006; Álvaro-Fuentes et al. 2009), the C sequestration rate is calculated by dividing the variation in SOC by the number of years during which the simulation has been made. However, this value has been defined as C storage or CO_2 balance (Feller and Bernoux 2008), and is currently a debated method, since the increase in soil C is not linear but rather rises rapidly in the first few years and then declines over time (Ingram and Fernandes 2001).

The increased SOC concentration and its fixation by the soil measured in the CC of the present work are very high in comparison with the values registered in other works (Smith 2008; Álvaro-Fuentes et al. 2009; Nieto et al. 2010). This is due firstly to the fact that the results are expressed for the first year after the change in management. In agreement with Ingram and Fernandes (2001), the rise in SOC declined with time as the soil approached a new state of equilibrium. Figure 3 shows that the equilibrium tended to be reached earlier at the site that presented a lower annual rate of C increase. Secondly, the C-fixation rates depended on the climatic characteristics of the study zone. Vleeshouwers and Verhagen (2002) indicated that the highest ranges of C fixation related to the supply of organic debris were registered in southern Europe (including Spain), coinciding with the low organic-carbon contents and dry summers, which reduce decomposition of organic matter and therefore the increases are more rapid.

Conclusions

The use of SOC models helps us to understand the C dynamics in the soil-plant-atmosphere system and then to predict possible alterations in the CO_2 exchange. Our study investigated the influence of land use and management on C dynamics using the RothC model, providing unpublished data for olive groves. In the Mediterranean area, the land-use change from native vegetation to cultivation promoted soil degradation, resulting in low SOC contents. This decrease was associated with the T system, characterized by low plant-debris input, greater organic-matter mineralization, and higher soil erosion. The final concentration of SOC for the three locations of this study depended mainly of the land relief and the clay content, with a maximum loss of 90 %. The RothC satisfactorily predicted the C input for the Mediterranean native vegetation areas, but overestimated the SOC of tilled soils after the land-use change. The difference between modelled and measured data was higher in areas where erosion appeared to be higher. These results suggest that soil loss affects the physically protected C (inert organic matter), so that it is advisable to devise a new parameter in the model to include these losses.

The use of CC in the grove increased the SOC due to higher C inputs to the soil and the lack of tillage. The plants of the CC was responsible for between 44 and 85 % of carbon input for the uppermost 15 cm of the soil, while for the bulk soil the belowground contribution of the olive tree was higher than 50 %. The vegetation of the CC involved a previous fixation of atmospheric CO_2 by photosynthesis, which was left as debris on the ground when the plant died. The CC resulted in C storage during the first year of $4.02 \pm 1.65 \text{ Mg C ha}^{-1} \text{ year}^{-1}$, and a total C fixation by the soil of $5.91 \pm 2.06 \text{ Mg C ha}^{-1} \text{ year}^{-1}$. These high rates were favoured by the climatic factors typical of the Mediterranean area. Over time, the location with higher C storage and fixation had the most C input. For this soil-management change, RothC gave good estimations. The use of CC in Mediterranean olive groves is a suitable strategy to decrease the concentration of CO_2 in the atmosphere.

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