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Improvement of soil carbon sink by cover crops in olive orchards under semiarid conditions. Influence of the type of soil and weed

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Abstract

The olive tree is one of the most important crops in Spain, and the main one in the region of Andalusia. Most orchards are rain-fed, with high slopes where conventional tillage (CT) is the primary soil management system used. These conditions lead to high erosion and a significant transport of organic carbon (OC). Moreover, soil tillage accelerates the oxidation of the OC. Cover crops (CC) are the conservation agriculture (CA) approach for woody crops. They are grown in-between tree rows to protect the soil against water erosion and their organic residues also help to increase the soil carbon (C) sink. Soil and OC losses associated to the sediment were measured over four seasons (2003-07) using micro-plots for the collection of runoff and sediment in five experimental fields located in rain-fed olive orchards in Andalusia. Two soil management systems were followed, CC and CT. Furthermore, the changes in soil C in both systems were analyzed at a depth of 0-25 cm. CC reduced erosion by 80.5%, and also OC transport by 67.7%. In addition, CC increased soil C sink by 12.3 Mg ha^{-1} year^{-1} of carbon dioxide (CO_2) equivalent, with respect to CT. Cover crops in rainfed olive orchards in a Mediterranean climate could be an environmental friendly and profitable system for reducing erosion and increasing the soil C sink. However, C fixing rate is not regular, being very high for the initial years after shifting from CT to CC and gradually decreasing over time.

Additional key words: carbon fixation; climate change; conservation agriculture; soil protection; woody crops.

Introduction

Olive trees (*Olea europaea* L.) are native to the Mediterranean basin; however, it is in Spain where they have reached their greatest development and implantation (Civantos, 2008). In many Spanish regions, this tree is almost the only crop. In Andalusia, olive orchards cover a surface area that exceeds 1.5 million hectares, 60.2% of Spain's total growing area (MARM, 2010). Andalusia produces 39% of the world's olive oil and 24% of the world's table olives (IOOC, 2011). The crop represents 25% of Andalusia's agricultural production (CoAP, 2003). Most plantations are rain-fed, occupying 74.5% of the total olive cultivated area in Andalusia (CoAP, 2003) and are normally grown on relatively poor soils with steep slopes. Approximately 12% of the olive trees in Andalusia are planted on slopes greater than 25%, and 24% to 46% of the trees are on hills with an inclination between 15-25% and 5-15%, respectively. Only 18% are found on slopes of less than 5% (CoAP, 2003). These facts, together with a Mediterranean climate with lengthy periods of drought followed by frequent torrential storms, result in high soil losses as intensive tillage is the most common soil management system (Pastor, 2004; Gómez, 2005; Vanwalleghem *et al.*, 2010). During high intensity

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Abbreviations used: C (carbon); CA (conservation agriculture); CT (conventional tillage); OC (organic carbon); OM (organic matter); SOC (soil organic carbon).

events, these losses can cause erosion rates higher than 400 Mg ha^{-1} (Vanwalleghem & Giráldez, 2008).

Although soil loss associated tillage is the greatest environmental problem of rain-fed olive farming, nowadays, the loss of soil organic carbon (SOC) associated with ploughing is considered a serious threat. Indeed, not only for the continuity of crop production, as it reduces soil fertility, but also for the environment, as a result of high CO_2 emissions (Kassam *et al.,* 2012).

Several consequences of with soil tillage cause a decrease in SOC content due to organic matter (OM) mineralization. These are: aeration of the soil profile, breaking up, depletion and instability of the aggregates, increase in the proportion of macropores to micropores and severe reduction of the contribution of organic residue (Lal & Kimble, 1998; Jones *et al*., 2004; Bronick & Lal, 2005; Pulleman *et al*., 2005). These effects significantly reduce soil fertility and productivity and increase CO_2 emissions into the atmosphere, through SOC oxidation. Moreover, global CO_2 releases associated with erosion are estimated to be between 0.8 and 1.2 Gt year^{-1} (Lal, 2003).

OM is basically composed of carbon (C) and is widely recognized as a stabilizing compound of the soil structure and a nutrient reservoir for plants (Carbonell *et al*., 2010). During the second half of the 20th century, the intensification of agricultural systems, especially soil tillage, caused an important decrease in SOC (Izaurralde *et al*., 2001; Sperow *et al*., 2003; Triplett & Dick, 2008). The global amount of C accumulated in the soil was estimated to be around 2,500 Gt, with 62% found in the SOC and the rest as inorganic C. This reserve is double the amount found in the atmosphere (760 Gt) and 2.8 times that of the biotic mass (560 Gt). Inadequate practices are estimated to had been responsible for the loss of between 55 and 78 Gt of C from the soil, which corresponds with its potential capacity as a C sink. However, the real capacity to store C in the soil was found to be between 50% and 66% of its potential capacity (Lal, 2004).

C sequestration requires the transfer of atmospheric C to storage in such a way that it is not immediately reemitted. Given that the average degradation time of OM in the soil is in the order of centuries, even millenniums (Paul *et al*., 1997; Torn *et al*., 1997), increasing SOC using appropriate soil management practices is an interesting option, since the strategy for sequestering C in the soil is economically and environmentally efficient.

Conservation agriculture (CA) in woody crops accumulates C in the soil for several reasons. The first is to reduce output of OM adsorbed to sediment by decreasing water erosion (Gómez *et al*., 2005; Francia *et al*., 2006; Ordóñez *et al*., 2007a). The second to increase OM content by contributing a great amount of plant residue (Moreno *et al*., 2009). The third is to reduce the mineralization of OM by not aerating the soil (Oades, 1993; Franzluebbers, 2002).

In spite of the foregoing advantages, there are still many questions regarding the role that soil management systems could play in atmospheric C sequestration (Smith *et al*., 2005; Pyke & Andelman, 2007; Ovando & Caparrós, 2009). The objective of this study is to quantify the efficiency of cover crops (CC) as a method for improving soil capacity as a C sink in rainfed olive orchards under semiarid conditions in Southern Spain.

Material and methods

Experimental fields

The study was conducted over four seasons (2003-07) in five experimental fields distributed in different rain-fed olive regions in Andalusia: two in the province of Cordoba (Fields 1 & 2), and one in the province of Jaen (Field 3), Seville (Field 4) and Huelva (Field 5). The fields include most soil types and olive growing systems and the most common practices under CA. Therefore, they represent the reality of olive production in Andalusia, obtaining results that are very close to real values, when extrapolating the data to the total crop in this region. Table 1 presents the most relevant characteristics of the fields. During the first year of study, samples were taken from all fields to determine the physico-chemical characterization of the first 60 cm of soil. Table 2 provides a summary of the results. Differences were observed in the textures of the experimental fields and especially in the organic carbon (OC) content, which was influenced by the granulometric composition of the soil, the weather and the different tillage systems used by the olive grower.

Experimental design and treatments

In each field, three plots under CA were established in the cover of the orchard and the tillage plots were established in areas designed for this purpose. In order to calculate the temporal evolution of the SOC, three

Table 1. Main characteristics of the experimental fields

	Field 1	**Field 2**	**Field 3**	**Field 4**	**Field 5**
Province	Cordoba	Cordoba	Jaen	Seville	Huelva
Frame (m^2)	8×8	Undefined	12×12	8×6	6×8
Age (years)	12	>60	>70	10	9
CC[a]	Spontaneous	Spontaneous	Sown	Spontaneous	Spontaneous
CC control	Mowing+tillage	Grazing	Herbicide	Weed trimmer	Weed trimmer
Slope (%)	15.6	21.6	18.6	6.2	8.7
Soil type	Calcic Haploxerept	Ruptic-Lithict Xerorthent	Calcic Haploxerept	Typic Calcexerept	Typic Haploxerept
Coordinates	37° 38’ 18” N 4° 46’ 01” W	38° 08’ 26” N 4° 46’ 01” W	37° 49’ 42” N 3° 57’ 36” W	37° 34’ 38” N 5° 21’ 37” W	37° 21’ 14” N 6° 23’ 42” W

[a] CC: cover crops.

pairs of sub-plots (6 m^2) were selected for each soil management system, conventional tillage (CT) and CC, in every experimental field. The sub-plots were distributed in a completely randomized block design. So as to ensure accurate results, runoff diverters were installed in the tillage plots to prevent entry of water and sediment that came from the CC. Three micro-plots (1 m^2) were selected in each experimental field, for collecting runoff and sediment, and measuring soil loss and OC adsorbed in the sediment, as was described in detail by Rodríguez-Lizana *et al*. (2005). The micro-plots were distributed in a completely randomized block design.

After every rainfall event, two sub-samples of water and sediment were taken from each micro-plot field in a 1.3 L container. Prior to taking of sub-samples, the runoff and sediment collected in the containers were shaken to ensure a homogeneous distribution of sediment. The CC were managed differently in each farmer’s field, so timing and type of cover control were different, depending on their local practices, as Table 1 shows. Tillage inside the micro-plots under CT was performed according to the vegetative state of the grass and the local practices in the area under study. In order to perfom this task, a rotary tiller was used to plough the soil to a depth of 20-25 cm.

Table 2. Main physico-chemical characteristics of the experimental fields

Field	**Depth (cm)**	**pH**	**OC[a] (%)**	**CO_3^{-2} (%)**	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Texture**
1	0-20	8.09	0.65	78.6	21.3	45.8	32.9	Clayey-loam
	20-40	8.26	0.51	78.6	25.9	45.8	28.3	Clayey-loam
	40-60	8.25	0.76	67.0	27.1	39.2	33.7	Clayey-loam
2	0-20	6.61	1.54	8.5	37.6	57.6	5.2	Silty-loam
	20-40	6.61	0.94	0.4	34.2	60.1	5.7	Silty-loam
	40-60	6.66	0.55	0.4	47.4	47.5	5.1	Sandy-loam
3	0-20	7.98	0.55	48.0	27.0	39.8	33.2	Clayey-loam
	20-40	7.89	0.69	44.8	25.3	43.9	30.8	Clayey-loam
	40-60	8.08	0.35	49.6	30.4	43.1	26.5	Loamy
4	0-20	8.29	0.88	28.2	42.6	33.2	24.2	Loamy
	20-40	8.21	1.21	28.1	36.2	32.8	31.2	Clayey-loam
	40-60	8.23	1.06	34.2	37.6	34.9	28.3	Clayey-loam
5	0-20	8.05	0.89	20.1	28.4	41.8	29.8	Clayey-loam
	20-40	8.09	0.79	20.9	27.4	43.1	29.3	Clayey-loam
	40-60	8.25	0.55	33.4	24.7	47.6	27.7	Clayey

[a] OC: organic carbon.

At the beginning of the experiment and after 4-years of study, a comparative balance of SOC was carried out for both soil management systems. As the surface layers show the most significant changes after the first years of CC implementation (Jarecki & Lal, 2005); samples were taken at the depths of 0-2 cm, 2-5 cm, 5-10 cm and 10-25 cm. Each sample was composed of 3 sub-samplings from each sub-plot. At the same time, bulk density of the soil was calculated at two depths (top 0-6 cm and 19-25 cm) in each soil management system and experimental field, using a hollow stainless steel cylinder (height 60 mm, diameter 52 mm, volume 127.423 cm^3). In addition, prior to mowing the CC, the amount of biomass generated was calculated by taking annual samples in four replications from an area of 0.25 m^2. This task was only performed in CA fields, as CT eliminates the soil cover due to plough passes.

Climate conditions of the study area

The study area corresponds to a xeric moisture regime, according to Soil Taxonomy (USDA, 1998). The climate is characterized by a cold and humid period that coincides with the autumn and winter, when 80% of the rainfall occurs; and a very hot and dry period during the spring and summer. The temperature regime is thermic. Table 3 shows that temperatures were more homogeneous than rainfall, which recorded differences of more than 200 mm year^{-1} in some of the experimental fields with respect to the mean total precipitation.

Laboratory analysis

Runoff water with sediment lost were oven-dried at 110°C to obtain sediment dry weight, after which the concentration of sediment was calculated by extrapolating the total runoff volume. Dried soil and sediment were sieved through a 2 mm sieve, and then fine earth was used to determine SOC content using the oxidation method proposed by Walkley & Black (1934). After ascertaining the SOC content of each soil, using Eq [1], the amount of CO_2 equivalent can be calculated using Eq [2]:

$$\text{OC (Mg ha}^{-1}\text{)} = \text{OC (g kg}^{-1}\text{)} \cdot \rho_a \text{ (Mg m}^{-3}\text{)} \cdot \text{D (m)} \cdot 10{,}000 \text{ (m}^2\text{ ha}^{-1}\text{)} \cdot 1 \text{ kg}/1{,}000 \text{ g} \quad [1]$$

$$CO_2 \text{ (Mg ha}^{-1}\text{)} = \text{OC (Mg ha}^{-1}\text{)} \cdot 3{,}67 \quad [2]$$

where OC: soil organic carbon, ρ_a: soil bulk density, D: soil depth, and CO_2: carbon dioxide.

The plant residue was washed with distilled water to eliminate impurities and then was dried for two days in a forced-air oven at 65°C to obtain the dry weight.

Statistical analysis

Version 8 of the program Statistix was used for the statistical analysis of the data. Three factors were considered: plot, block and treatment. The comparison of means between these factors was performed using the Tukey test.

Results and discussion

Presumably, CA systems would produce an increase in the bulk density of the soil due to absence of tillage and the effects of repeated machinery traffic. However, Fig. 1 does not show important differences in the soil bulk density for CC and CT systems, as also observed Álvarez & Steinbach (2009). Soils under CA registered

Table 3. Average temperatures (°C) and precipitation (mm) and their standard deviation from 2003 to 2007

Field		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
1	Temp	7.4 ± 1.0	8.6 ± 1.6	11.9 ± 0.7	14.4 ± 1.4	18.0 ± 3.5	24.5 ± 1.6	27.4 ± 0.4	26.8 ± 0.6	22.5 ± 0.6	16.9 ± 1.7	11.5 ± 1.2	8.0 ± 0.5	—
	Rain	41 ± 34	79 ± 21	71 ± 40	40 ± 31	53 ± 41	5 ± 5	2 ± 3	2 ± 4	29 ± 11	95 ± 50	37 ± 37	47 ± 30	500 ± 120
2	Temp	6.7 ± 1.1	7.1 ± 1.4	10.1 ± 0.9	12.4 ± 1.1	18.8 ± 2.1	23.0 ± 1.8	26.2 ± 0.5	25.5 ± 0.8	21.9 ± 1.6	15.5 ± 1.2	10.5 ± 1.2	6.9 ± 0.3	—
	Rain	36 ± 26	57 ± 22	60 ± 36	60 ± 14	52 ± 36	4.4 ± 2.4	0 ± 0	8 ± 14	36 ± 27	146 ± 97	54 ± 43	53 ± 28	565 ± 177
3	Temp	8.0 ± 1.0	9.3 ± 1.7	12.7 ± 1.0	15.6 ± 1.4	20.4 ± 2.2	26.1 ± 1.7	29.0 ± 0.4	28.3 ± 0.8	24.1 ± 0.7	18.3 ± 1.0	12.4 ± 1.2	8.7 ± 0.3	—
	Rain	21 ± 21	63 ± 21	54 ± 32	52 ± 36	45 ± 42	8 ± 9	1 ± 1	8 ± 10	21 ± 13	72 ± 52	38 ± 32	34 ± 21	416 ± 119
4	Temp	8.9 ± 1.4	10.1 ± 1.8	13.5 ± 0.6	16.3 ± 0.7	20.6 ± 1.7	25.2 ± 1.3	27.4 ± 0.8	27.0 ± 0.7	23.8 ± 0.8	18.6 ± 0.6	13.2 ± 1.3	9.5 ± 0.4	—
	Rain	40 ± 44	68 ± 26	46 ± 30	33 ± 16	63 ± 53	2 ± 3	0 ± 0	14 ± 18	34 ± 24	79 ± 73	52 ± 43	57 ± 42	501 ± 138
5	Temp	10.1 ± 0.9	10.9 ± 1.1	13.6 ± 0.7	15.6 ± 0.9	19.4 ± 1.5	23.5 ± 1.7	26.0 ± 0.8	25.7 ± 1.1	22.7 ± 0.6	18.6 ± 0.6	14.0 ± 0.8	10.9 ± 0.5	—
	Rain	50 ± 50	82 ± 70	57 ± 41	42 ± 31	36 ± 39	11 ± 20	0 ± 0	17 ± 33	18 ± 22	117 ± 72	59 ± 47	46 ± 53	535 ± 212

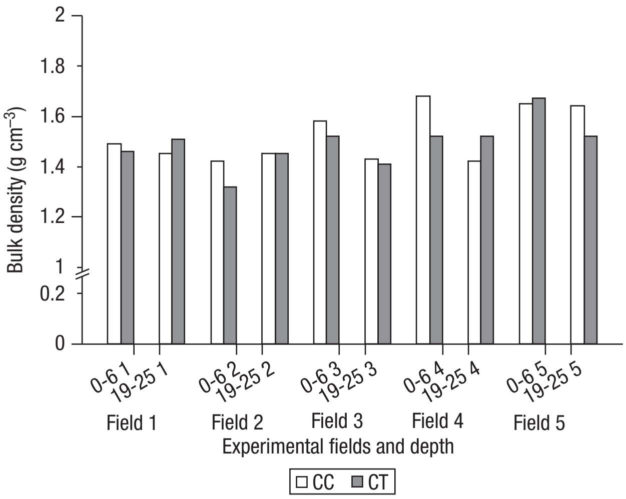

Figure 1. Bulk density of the different experimental fields and depths sampled. Sampling season: 2003-04.

slightly higher bulk density values on the surface (0-6 cm). In all experimental fields, average bulk density increased by 4% with the CC system, whereas bulk density was distributed more homogeneously under the CT system. This result coincides with those published by Birkás *et al*. (2004), who observed that CA displayed a compaction peak at a depth of 3-5 cm. This compaction could increase erosion processes, as Fullen (1985) observed , but the plant protection reduced soil erosion in CC.

Fig. 2 shows the relationship between soil loss and OC loss adsorbed to the sediment during the four seasons of the study for all the experimental fields and treatments. A positive relationship can be observed between soil loss and OC output in both management systems. The results showed that for CC, erosion was always below 2 Mg ha^{-1} and OC losses less than 40 kg ha^{-1}, with an R^2 of 0.87. Meanwhile, for CT erosion (< 6 Mg ha^{-1}) and OC losses (< 80 kg ha^{-1}) were higher than in CC, also with a high R^2 of 0.83. It is worth highlighting the huge erosion and OM losses measured with some rainfall events under the CT system, which is very common in this region and these crops (Martínez-Mena *et al*., 2012).

Table 4 shows the average annual accumulated erosion and OC loss over four seasons, as well as the decrease caused by CA compared to CT. In general, the CC system reduced soil and OC loss, whereas the CT system increased them in all experimental fields. Relative to the CT system, the fields that recorded most erosion were normally the fields with the greatest OC loss *i.e.,* Field 3, with 8.2 Mg ha^{-1} year^{-1} and 80.9 kg ha^{-1} year^{-1} respectively, followed by Field 5 (with 3.66 Mg ha^{-1} year^{-1} and 43.73 kg ha^{-1} year^{-1}) and Field 4 (with 2.46 Mg ha^{-1} year^{-1} and 49.04 kg ha^{-1} year^{-1}). Nevertheless, this did not happen with the OC in Fields 4 and 5, because the Field 4 had a greater OC concentration on the surface than Field 5 in the CT system (Fig. 3). With regard to the CC system, Field 5 contributed the largest reduction in soil loss *i.e.,* 91.6% in comparison to the CT system, followed by 89.5%, 86.0%, and 83.6% for Fields 2, 4 and 3, respectively; while the lowest reduction in soil loss was 51.7% observed in Field 1. On the other hand, Field 2 displayed the highest reduction in OC loss *i.e.,* 80% in comparison to CT system, followed by 75.0%, 72.1%, and 66.4% for Fields 4, 5 and 3, respectively. The lowest reduction in OC loss was 45.0%, observed in Field 1. In general, the average reduction in OC output and

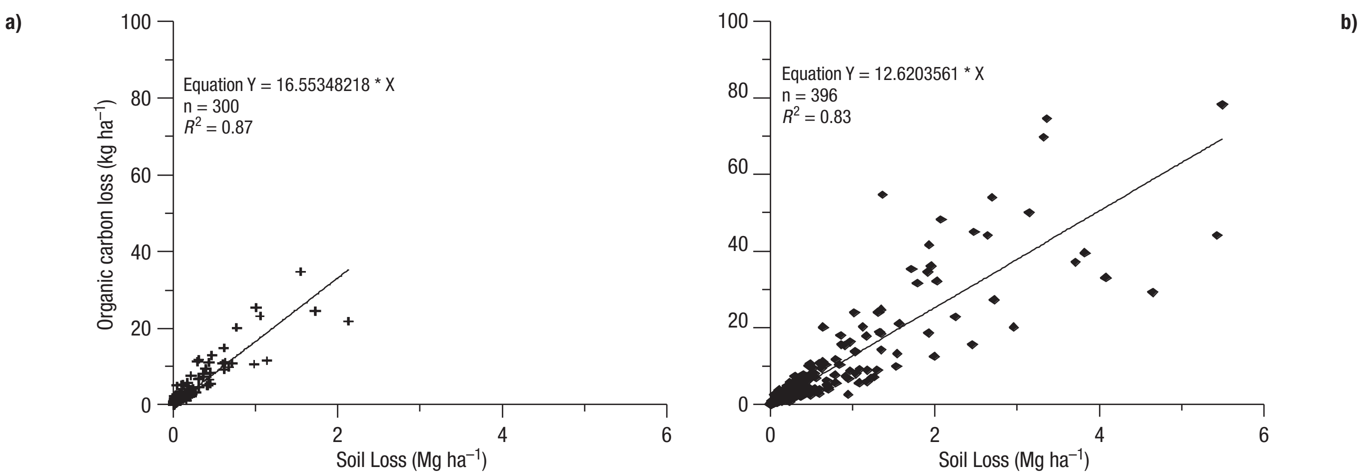

Figure 2. Correlation between soil loss and organic carbon (OC) loss adsorbed to sediment for the whole experimental fields and study period (2003-07): (a) cover crops (CC), (b) conventional tillage (CT).

Table 4. Average annual soil and organic carbon (OC) losses and their reduction percentages from 2003 to 2007

		Field 1	Field 2	Field 3	Field 4	Field 5
Soil loss (kg ha^{-1})	CC[a]	616.60	219.35	1,350.00	345.44	309.21
	CT[b]	1,276.14	2,079.29	8,216.13	2,461.01	3,662.70
	Reduction (%)	51.7	89.5	83.6	86.0	91.6
OC loss (kg ha^{-1})	CC	8.78	8.47	24.19	12.28	12.19
	CT	15.95	42.27	80.91	49.04	43.76
	Reduction (%)	45.0	80.0	66.4	75.0	72.1

[a] CC: cover crop. [b] CT: conventional tillage.

erosion in the five fields was 67.7% and 80.4% respectively; this reduction was less than that observed by Gómez *et al.* (2011) under similar conditions, especially for the OC (95.2%), and slightly lower for erosion (97.4%). With regard to erosion and OC loss, the higher the reduction in erosion, the greater the reduction in OC output from the system.

C inputs favored by the presence of plant residues on the surface and the lower output of OC associated with sediment, made greater OC concentration in the soil in the conservative system. As observed in Fig. 3, which shows the variation in OC content versus depth, in the top layer sampled (0-2 cm), 4 out of 5 fields showed statistically significant differences in favor of CC. Concentrations in CC were above 1.2% in the first 5 cm in all cases, which is the amount recommended in Andalusia as the minimum value for integrated production systems (BOJA, 2002). These results are simi-

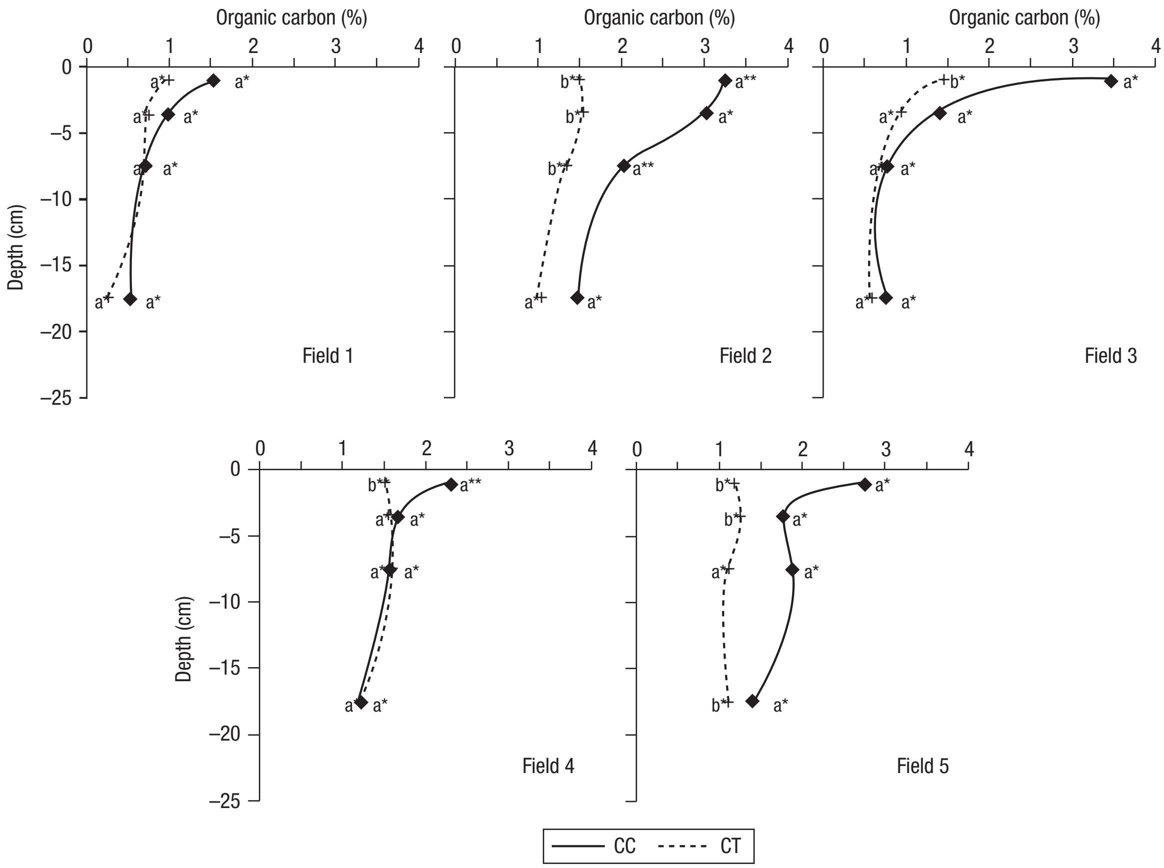

Figure 3. Spatial variation of the OC content (%) *versus* depth for the 2006-2007 sampling season. Different letters indicate significant differences with the Tukey test for * $p \leq 0.05$ and ** $p \leq 0.01$.

Table 5. Standard deviation of the organic carbon concentration in the soil for the experimental fields and depths sampled

Field		Season 2006-07				
		0-2 cm	2-5 cm	5-10 cm	10-25 cm	0-25 cm
1	CC[a]	± 0.68	± 0.79	± 0.82	± 0.90	± 0.76
	CT[b]	± 0.52	± 0.47	± 0.52	± 0.56	± 0.25
2	CC	± 0.76	± 1.09	± 0.69	± 0.97	± 0.54
	CT	± 0.51	± 0.19	± 0.65	± 0.60	± 0.47
3	CC	± 2.40	± 1.11	± 0.72	± 0.84	± 0.44
	CT	± 0.45	± 0.72	± 0.13	± 0.10	± 0.11
4	CC	± 0.76	± 0.40	± 0.43	± 0.60	± 0.42
	CT	± 0.65	± 0.27	± 0.59	± 0.08	± 0.12
5	CC	± 0.94	± 0.20	± 1.06	± 0.11	± 0.25
	CT	± 0.28	± 0.22	± 0.12	± 0.18	± 0.12

[a] CC: cover crop. [b] CT: conventional tillage.

lar to those obtained by Castro *et al*. (2008) and Gómez *et al*. (2009) for olive groves in Andalusia.

As profile depth increased, differences in the content of SOC decreased. In fact, below 10 cm, statistically significant differences were observed in only one of the fields (5), because the amount of debris contributed by the roots of the plants may not be as great as the canopy, and it is distributed over a larger area. Therefore, the top layer experienced a greater and faster increase in OC not only in olive orchards, but also in different arable crops (Jarecki & Lal, 2005; Ordóñez *et al*., 2007b).

As regard the dispersion of the results, Table 5 summarizes the standard deviation of OC at the four depths for the five experimental fields during the 2006-2007 sampling season. Regardless of soil depth, the highest standard deviation values were observed in the soils using the CC system. Ploughing homogenized the profile and lessened the spatial variations of its components. These data coincide with those observed by Hernández *et al*. (2005) under similar climatological conditions.

For the total profile sampled (0-25 cm), most of the fields showed important differences in OC content between CC and CT. Fig. 4 shows two fields (2 and 5) demonstrating significant differences in favor of CC. These results coincide with those obtained by other authors for olive groves (Hernández *et al*., 2005; Gómez *et al*., 2009; Ramos *et al*., 2010).

Soil capacity to store OC primarily depends on climatic and edaphological conditions (Miller *et al*., 1994); however, the soil management system can play a decisive role in agricultural land (Hernanz *et al*., 2002), as well as the local conditions of the farm itself. Some authors, such as Arrouays *et al*. (2006), found a positive correlation between clay content and the amount of SOC. In our study, and considering the 0-25 cm layer, the highest values of OC were observed in Fields 2, 5 and 4, whose soils registered a lower percentage of clay than that estimated for Fields 1 and 3 (Table 2 and Fig. 4). In these cases, the climatic conditions affecting the study area could have been more important in the evolution of SOC than its edaphological characteristics. The soils with CC in Field 2 warrant a special mention, recording higher OC values for all of the depths sam-

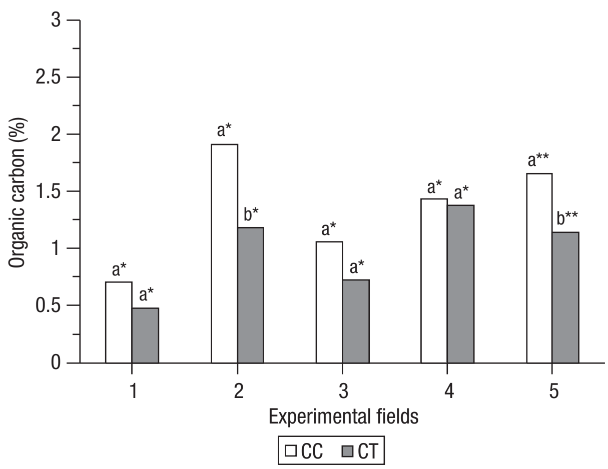

Figure 4. Variation in OC content between the different experimental fields for the total profile sampled (0-25 cm) for the 2006-2007 sampling season. Different letters indicate significant differences with the Tukey test for * $p \leq 0.05$ and ** $p \leq 0.01$.

pled, possibly due to the fact that the cover was controlled by grazing, which contributed a large amount of C in the form of livestock excrement, further raising OC content. These results coincide with those observed by Quiroga *et al*. (2009). It must also be taken into account that this field registered the bigger precipitation, favoring the activity of microorganisms, which decompose the organic residue. The lowest OC concentrations under both soil management systems were obtained in Field 1. This farm was run under organic farming, increasing the number of tillage passes over the soil to control the grass in CT. In addition, both management systems used the application of vinasse, a liquid organic fertilizer, which is a product of grape fermentation. Application required deep ploughing and subsequent injection into the soil. It should be pointed out that vinasse was not applied at the OC sampling points, in order to prevent any alteration to the values caused by the distorting effect of vinasse application on C fixation. However, a tillage pass was made. Therefore, the increase in soil tillage and tillage depth favored the breaking down of aggregates and the oxidation of the OC that they protected in both systems (Trebrügge & Düring, 1999).

The production of biomass, as shown in Fig. 5, produced very different results. The average biomass production of the CC primarily consisting of broadleaf weeds (Fields 1, 2 and 4) ranged between 3.5 and 4.5 Mg ha^{-1} during the three sampling years. The CC primarily made up of *gramineae* produced much more plant mass, approximately 7 Mg ha^{-1} in Field 3 and 9 Mg ha^{-1} in Field 5. These values are comparable to the 5-10 Mg ha^{-1} biomass produced in vineyards in California measured by Bugg *et al*. (1996) and the mean values observed by SAN (1998) for different types of cover, 1.5-11 Mg ha^{-1}. It is worth highlighting that the fields with *gramineae* CC (3 and 5) display the highest surface concentrations of OC of all five fields studied, together with Field 2, for the previously mentioned reasons.

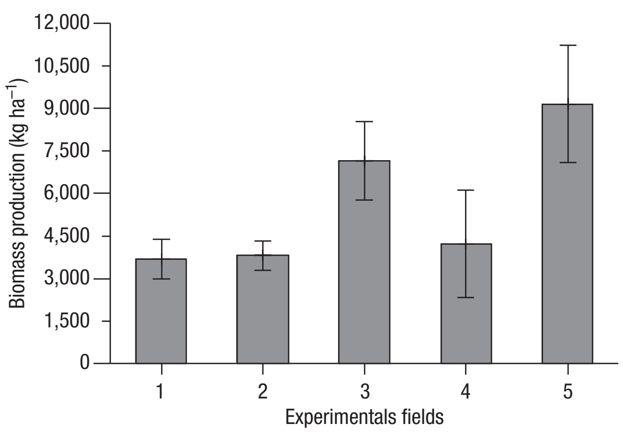

Figure 5. Average annual biomass production and its standard deviation for the different experimental fields. Sampling seasons: 2003 to 2007.

Table 6 shows the CO_2 equivalent accumulated in the soil at the start of the study and the CO_2 equivalent after four years for the different depths sampled and experimental fields. Differences were also observed between the soil management systems studied. At the start of the experiment, the amount of CO_2 equivalent accumulated in the soil was similar for both management systems and the differences observed were less than 10%, except for Field 4, where it was 12.09%, with a mean of 5.71% between the five fields. For the total profile sampled, after four years in the five experimental fields, CC increased CO_2 equivalent content with respect to the reference period (2003) in all the experimental fields, with an average value of 15.88 Mg ha^{-1} year^{-1}. CT increased the sink effect of this compound in three of the five fields. However, overall, a lower increase of 3.57 Mg ha^{-1} year^{-1} was obtained. These values are higher than those measured by González-Sánchez *et al*. (2012), in similar conditions (1.54 Mg ha^{-1} year^{-1}). The reason could be related to a shorter period in our case (4 year respect 10 year). In addition, in our study the cover crops formed with grass constituted the largest C sink, unlike in González-Sánchez *et al*. (2012), where this alternative produced the worst results.

Fig. 6 shows the deviation respect to the mean of the average increase of CO_2 equivalent observed in the different experimental fields compared to the reference period (2003-04 seasons), for CC and CT, studied individually and collectively. It shows how the deviation is small for CC. Field 1 was slightly below the mean, and Field 5 was slightly above it. In the case of tillage, the situation changes, exhibiting a much greater deviation. Experimental Fields 1 and 2 displayed a negative deviation (below the mean), since these fields underwent deeper and harsher tillage, with inversion of the soil profiles. However, less aggressive tillage was used in the other three fields, with less tillage trips and no overturning, resulting in a positive deviation (above the mean). Studying both management systems together revealed how CC always registered positive deviations with respect to the mean, except in Field 1; as this system was tilled to inject vinasse as previously explained.

Table 6. CO_2 equivalent fixation (Mg ha^{-1}) for the different depths sampled and experimental fields

Field	System	2003-04	2006-07				
		0-25 cm	0-2 cm	2-5 cm	5-10 cm	10-25 cm	Δ[c] 0-25 cm
1	CC[a]	82.74	16.32	15.98	18.91	42.72	11.19
	CT[b]	85.01	10.56	11.77	19.15	23.96	–19.58
	Difference	–2.27	5.76	4.21	–0.24	18.76	30.77
2	CC	178.19	31.45	43.69	48.88	126.96	64.16
	CT	186.00	15.57	24.01	34.80	81.24	–30.39
	Difference	–7.81	15.89	19.69	14.08	45.82	94.55
3	CC	78.28	38.73	23.62	21.33	59.73	64.13
	CT	79.88	16.93	15.95	21.24	46.11	19.58
	Difference	–1.60	21.80	7.67	0.09	13.62	44.55
4	CC	127.80	25.80	28.15	43.80	95.64	65.59
	CT	139.89	18.87	28.95	49.87	103.36	61.16
	Difference	–12.09	6.93	–0.80	–6.07	–7.72	4.43
5	CC	127.80	33.42	32.27	56.99	117.85	112.52
	CT	132.59	14.57	23.14	34.07	101.44	40.63
	Difference	–4.79	18.85	9.13	22.92	16.19	71.89
Average		–5.71	13.85	7.98	6.16	17.33	49.24
Average cm^{-1}		–0.23	6.92	2.66	1.23	1.16	1.97

[a] CC: cover crop. [b] CT: conventional tillage. [c]Δ: Increase of CO_2 equivalent respect to the reference period (2003-04).

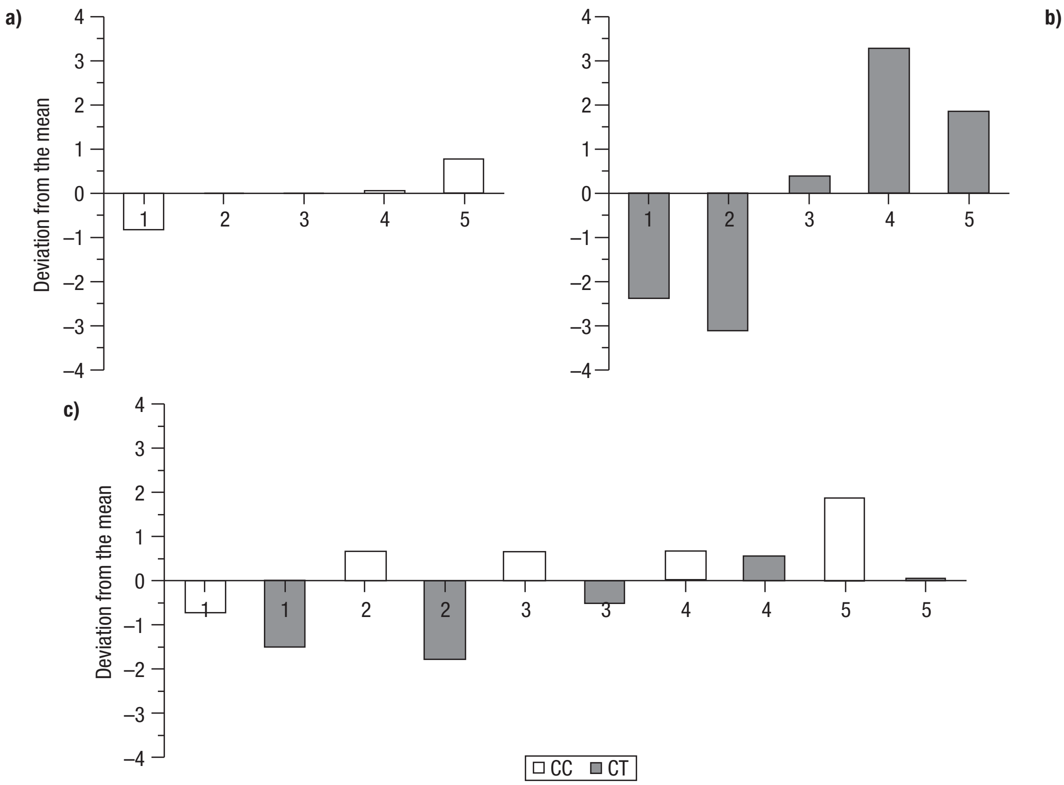

Figure 6. Deviation with respect to the mean of C increase in (a) cover crops (CC) and (b) conventional tillage (CT), individually and (c) collectively. Sampling season: 2006-07.

Under CT, all of the alternatives recorded zero or negative increases, except Field 4, due to the variation in the mineralization processes caused by flooded conditions, very common in this field (Castro *et al*., 2008). In relation to the increase in CO_2 equivalent provided by the CC compared to CT during the four years of study, it was observed that conservation systems increased the content of this compound by 1.97 Mg ha^{-1} cm^{-1} compared to CT. These data were higher than those obtained by Gómez *et al*. (2009) in a seven-year experiment (1.23 Mg ha^{-1} cm^{-1}), as like other author had found that the maximum sink effect is reached during the fifth year after the application of CA (West & Six, 2007), with the fixation speed decreasing since this period. The values obtained were slightly greater than those indicated by Sombrero & De Benito (2010) for extensive crops (1.59 Mg ha^{-1} cm^{-1}), although they took samples at greater depth (30 cm). The values are also much higher than those reported by Ordóñez *et al.* (2007b), who obtained an increase of 0.75 Mg ha^{-1} cm^{-1}, due to a longer study duration, 11 years, and depth sampled, 52 cm.

This study shows the capacity and effectiveness of CC in the conservation and improvement of soil quality. Under our experimental conditions, erosion decreased by an average of 80.5% and OC loss adsorbed to sediment decreased by 67.7%. In addition, the depth sampled, 0-25 cm, experienced a mean increase in OC of 38.1% with respect to tillage, with a more marked increase in the first 10 cm of soil, where it reached 47.5%. The CC formed with grass obtained the best results in regarding to increasing the C sink.

CC increased the sink capacity of C fivefold compared to CT, achieving an increase in CO_2 equivalent fixation with respect to the conventional system of 12.3 Mg ha^{-1} year^{-1} for the total depth sampled. According to the MARM (2011a), the CO_2 equivalent emissions in Andalusia for the year 2008 were 58,188 Gg, exceeding the maximum permissible value by 15,819 Gg required to fulfill the commitments made by this region in reference to the Kyoto protocol (MAGRAMA, 2012). According to the data obtained and taking into account the actual CC area of 518,659 ha (MARM, 2011b) in Andalusian olive groves, these soil conservation systems could annually fix 40.4% of the total gases needed to fulfill the commitments made.

However, we should be cautious with these figures, as other studies show how after a few years of practicing CA the fixation rate diminishes, while the sink effect continues to increase, albeit at a slower rate.

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