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Long-Term Effects of Residue Management on Soil Fertility in Mediterranean Olive Grove: Simulating Carbon Sequestration with RothC Model

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1. Introduction

Olive orchards are widely cultivated throughout the semiarid Mediterranean region. During olive growth a large quantity of vegetable residues are produced, either from the biannual pruning or from the olive-fruit cleaning in the oil mill, where the olive fruit is separated from the leaves, twigs and soil. These residues are generally discarded and the pruning debris is usually burned *in situ* or used for energy. Such practices not only release a large quantity of CO_2 into the atmosphere, but also fail to return to the soil the elements taken up by the tree. The use of crop residues is being widely debated today because of its impact on the soil degradation (Lal, 2008).

In Andalusian olive orchards, conventional agricultural practices such as tillage or non-tillage with bare soil also reduces the incorporation of plant remains into the soil, thus changing the quantity of soil organic carbon (SOC) in a variable way and accelerating erosive processes (Pastor, 2004). Nevertheless in recent years, the technique of shredding pruning debris and spreading the material over the orchard is becoming generalized as an alternative to burning. The residues left from fruit cleaning in the oil mill prior to extracting the oil, composed of leaves, green twigs, and superficial soil, can also be spread on the soil surface, returning to the soil the elements previously taken up by the tree. These new soil-management systems are an alternative for improving the soil quality and fertility in sustainable agricultural system (Ordóñez et al., 2001; Rodríguez-Lizana et al., 2008; Nieto et al., 2010).

Many studies on agricultural ecosystems, as reviewed by Jarecki & Lal (2003), have documented the changes in soil properties when the soil management shifts from tillage to cover crop, mainly the increase of SOC and nitrogen (N). The management of crop residues is an important aspect of conservation systems (Six et al., 1999; Paustian, 2000; Lal, 2008), since proper distribution on the ground surface reduces water losses and thus discourages soil erosion (Schomberg et al., 1999). Water and erosion constitute especially serious issues in zones that have a Mediterranean climate and can be only partially solved by recycling the crop debris (Rodríguez-Lizana et al., 2008).

When the soil includes great quantities of fresh plant material, it is necessary to separate the soil organic matter in order to quantify the SOC which is truly fixed. Some authors recommend methods to separate the water-floatable organic matter (FOM) from soil fractions according to size, using physical procedures such as ultrasound, together with a mixture of physical and chemical methods (Buyanovsky et al., 1994; Hevia et al., 2003). These latter procedures of fractionation appear to be more adequate when the residues added provide certain quantities of soil together with the plant debris.

According to Ingram & Fernandes (2001), the factors determining the current level of carbon in agricultural soils are the losses of soil and clay by erosion, the decline in plant debris, and the elimination of this. Franzluebbers (2002) proposed that soil quality is correlated with the stratification of the SOC. High SOC levels on the soil surface mitigate the direct impact of raindrops, protecting against sealing and the disruption of the soil structure (Hernanz et al., 2002).

Cultivation practices that improve soil quality and fertility, such as the use of crop residues, progressively change the physical and chemical properties of the soil (Rhoton et al., 1993; Ordóñez et al., 2001; Hernández et al., 2005). In addition to SOC and N, other nutrients have been made evaluated in this sense such as K^+ (Thomas et al., 2007), as has soil properties such as cation-exchange capacity (Oorts et al., 2003), or soil-water content (Rawls et al., 2003; Bescansa et al., 2006). The impact of different soil-management systems on soil properties have been studied for olive orchards (e.g. Hernández et al., 2005; Soria et al., 2005; Castro et al., 2008; Gómez et al., 2009) but only a few works have evaluated the effect of shredded olive-pruning debris (Ordóñez et al., 2001, Sofo et al., 2005; Rodríguez-Lizana et al., 2008).

Recently, agricultural soils have been identified as the major carbon pool in the context of its global cycle. Some authors (Jarecki & Lal, 2003; Hernández et al. 2005; Smith et al., 2008) have reported that strategies based upon changes in soil management in agricultural soils are potentially important in increasing carbon sequestration by the soil and in reducing the atmospheric CO_2 concentration. The main processes responsible for lowering current carbon levels in agricultural soils include erosion, tillage, and low inputs of agricultural residues (Lal, 2008; Álvaro-Fuentes et al., 2009). Some authors have emphasized that intensive tilling accelerates the decomposition of organic matter as result of the break-up of soil aggregates (Balesdent et al., 2000; Paustian et al., 2000) and contributes considerably to soil loss through erosion (Rodríguez-Lizana et al., 2008). Soil-management techniques that combine a restriction on tillage and the addition of organic residues are considered to be one potential way for improving soil properties and diminishing atmospheric CO_2 concentrations by storing carbon in the form of organic matter (IPCC, 2000; Jarecki & Lal, 2003).

The present work describes the effect on the soil after the spreading of olive-pruning debris together with the residues of the olive-fruit cleaning in two predominant soils in Andalusian olive orchards. In specific, study was made of the content, distribution, and stabilization of SOC (floatable and non-floatable in water) and N, the soil potential for carbon sequestration, as well as the effect of SOC in the K^+ content, bulk density (ρb), pH, cation-exchange capacity (CEC), and soil-water content (SWC) at -33 and -1500 kPa.

2. Material and methods

2.1 Field description

The study plot was located in the Cortijo El Empalme (Villacarrillo, Jaén), south-eastern Spain (38.175ºN, 3.15ºW) and is 812 m a.s.l. The climatic characteristics of the area are given in Table 1 (MAPA, 1989). The average annual rainfall was 550 mm, and average annual maximum and minimum temperatures of 37.0ºC and 2.8ºC, respectively. The natural vegetation is a perennial, sclerophyllous Holm oak (*Quercus ilex* L.) forest typical of the Mediterranean basin.

The orchard was comprised of adult olives (cv. picual) with 2-3 trunks and planting density of 82 trees ha^{-1}. The average slope is 3%. The orchard has underground drip irrigation and no fertilizers are applied to the soil. Following the WRBSR (FAO, 2006), the soils studied are classified as Chromic Calcisols (CLcr) and Calcic Vertisols (VRcc). The parent material is limestone in the CLcr and marls in the VRcc. The colour of the dry bare soils was dull brown (7.5 YR 5/4) in the CLcr and light grey (2.5 Y 7/1) in the VRcc.

Month	Temperature (ºC)			Rainfall	ETo
	Maximum	Minimum	Mean	(mm/month)	(mm/month)
January	10.9	3.7	7.3	69	33
February	13.3	4.5	8.9	74	46
March	17.9	5.6	11.8	68	87
April	20.3	8.6	14.5	59	110
May	25.8	13.4	19.6	52	154
June	30.1	18.6	24.4	25	170
July	35.5	20.6	28.1	6	211
August	34.1	20.3	27.2	8	182
September	28.6	17.0	22.8	24	122
October	22.2	11.6	16.9	53	81
November	14.8	6.4	10.6	47	43
December	11.3	4.0	7.7	67	30

Table 1. Maximum, minimum and average monthly air temperature, monthly rainfall and potential evapotranspiration (ETo) for the study area (MAPA, 1989)

Before the experiment, the soil-management system of the orchard was conventional tillage (T), consisting of two or three passes (0.20 m deep) with a disc harrow and cultivator, twice a year to control weeds. This tillage was applied only to the open gaps between the trees (50% of the total area of the grove). Under the tree canopy (UC), the soil was completely cleared every year using pre- and post-emergence herbicides. Dead leaves, dried fruit and twigs were removed by manual blowers and a mechanical sweeper without breaking the surface crust. The trees were pruned every 2 yr and the debris was burned.

The soil-management system was changed in 1996 on the CLcr and in 2000 on the VRcc to cover crop, whereby shredded olive-pruning and the residues from the olive-fruit cleaning (PD+CR) were spread between the trees. The ground was not tilled and all these residues remained on the surface. The biomass input was quantified by the use of a 30 x 30 cm metal frame tossed at random 40 times between trees. The mean annual input was 23.9 ± 14.3 Mg

C ha^{-1} yr^{-1}. This area was studied by Soria (2002) under traditional tillage in 1997, just before to the experiment was started. The clay types are given in Table 2.

Soil type	Illite	Montmorillonite	Kaolinite
Chromic Calcisols	77	13	10
Calcic Vertisols	45	36	19

Table 2. Clay type (%) for 0-30 cm depth, in each soil type according to Soria (2002)

2.2 Sampling and analytical methods

Random soil samples were taken in two different areas: (i) between trees in PD+CR soil after removing the superficial plant-residue layer and (ii) UC area where the soil was completely bare. In addition, to establish the time-zero conditions for the experiment, two neighbouring tilled olive groves were sampled. A trench of 50 x 100 x 50 cm was opened and the samples were taken at depth intervals of 0-2, 2-5, 5-10, 10-15, and 15-30 cm. Three replicate plots per type of soil and area were sampled. Soil samples were also taken from the pits to determine ρb, following the method of Blake & Hartge (1986), using a set of cylinders of 2, 3, and 5 cm high specifically manufactured for this purpose.

The soil samples were dried and sieved (2-mm grid size). In the fine-earth fraction, the following analyses were performed: the textural analysis was made by the pipette method of Robinson (Soil Conservation Service, 1972); the SWC at field capacity was extracted in a pressure plate at -33 kPa, and the moisture at the wilting point was measured at -1500kPa (Cassel & Nielsen, 1986); the assimilable K^+ was extracted with NH_4OAc 1M; and the CEC was determined by saturation in sodium and, prior to washing with alcohol, extraction by sodium adsorbed with NH_4OAc 1M (Soil Conservation Service, 1972); the pH was measured in a soil suspension in distilled water (1:2.5).

For the determination of the SOC, N, and $CaCO_3$ equivalent, the sample was ground again (0.125 mm). The content of the SOC was determined using the method of Tyurin (1951); water-floatable organic matter (FOM) and non-water-floatable organic matter (NFOM) was separated following the method described by Hevia et al. (2003); for the total nitrogen, the Kjeldahl method was used (Bremner, 1965); and the $CaCO_3$ equivalent was determined by a manometric method (Williams, 1948). For plant remains, carbon and N were determined by the same methods. The SOC, N, and clay contents per hectare were computed by multiplying the soil mass (i.e. bulk-density) by the depth and the SOC, N, and clay concentrations, respectively. The CO_2 emissions from burning residues were determined from the values of carbon concentration in pruning debris using a molecular-weight ratio (1.00 g C = 3.67 g CO_2) (IPCC, 2000).

2.3 RothC model

A detailed description of the model is given in Coleman & 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 (Figure 1) 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 CO_2 (lost from the system). The clay content of the soil determines the proportions that go to

CO_2 or to BIO + HUM. Each compartment, except for IOM, undergoes decomposition by first-order kinetics at its own characteristic rate, which is determined by using modifiers for soil moisture, temperature and plant cover.

The climatic 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. As no data for open-pan evaporation were available, the average values for monthly potential evaporation (converted to open-pan evaporation) were used (Coleman & Jenkinson, 1996). The IOM was calculated using the equation proposed by Falloon et al. (1998). The turnover time was calculated as the total organic carbon content except IOM divided by the annual input of carbon into the soil (Jenkinson & Rayner, 1977).

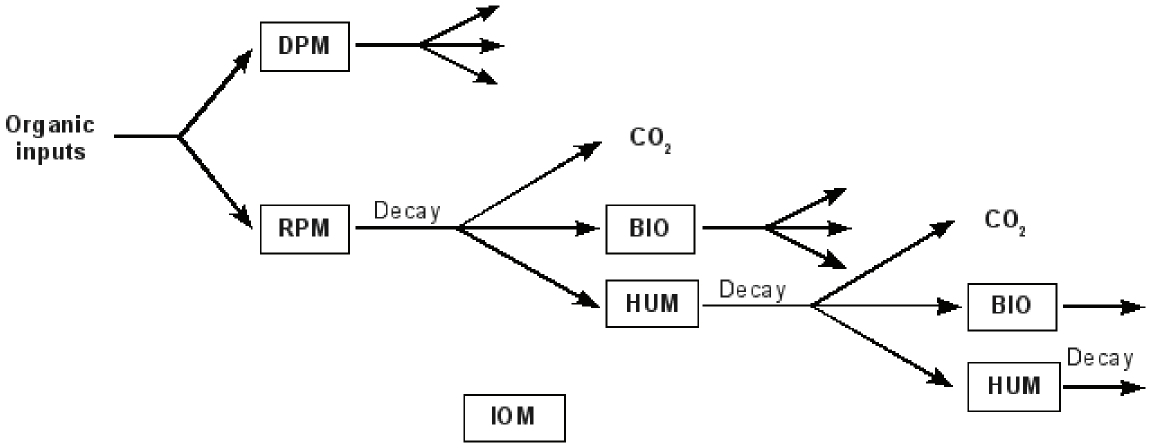

Fig. 1. Structure of the Rothamsted carbon model (from Coleman & Jenkinson, 1996)

RothC was designed to run in two modes: 'forward', in which known inputs are used to calculate changes in soil organic matter; and 'inverse', when inputs are calculated from known changes in soil organic matter. This model performed well for changing the carbon inputs to fit measured SOC values in other studies (Falloon & Smith, 2002). In our work, we used this model to assess the changes in the soil carbon content when soil management was changed from tillage to cover crop with pruning debris and the residues from the olive-fruit cleaning.

To run RothC at equilibrium (Coleman & Jenkinson, 1996), we needed to assume that the soils were in equilibrium (more than 30 yr with the same management). To determine the SOC value for the soil equilibrium under tillage, we sampled two neighbouring areas (one for each soil type) that ploughed the soils over the last 30 years. For the tilled olive grove, the soil was assumed to be in equilibrium. In this case, the RothC model was run iteratively in reverse to calculate how much organic carbon needs to enter a soil annually to give the measured amount of SOC. This value for the annual input of organic carbon was chosen to optimise the fitting between the modelled and measured data.

2.4 Statistical analysis

Data were analysed using SPSS v.10.0. Effects of the location and soil type for each variable were determined by one and two-way analysis of variance (ANOVA) at a confidence level of 95%. Tukey tests was performed for *post-hoc* comparisons between levels within each factor considered. Bartlett and Shapiro–Wilk tests were applied to check homoscedasticity and normality, respectively, to ensure that assumptions of the model were met. Spearman correlation was used to determine the degree of dependence between the SOC and other variables.

3. Results

3.1 Textural analysis, ρd, $CaCO_3$ and pH

Table 3 presents the results from the textural analysis, the percentage of gravel in the soils studied, ρb, $CaCO_3$ content, and pH. The gravel content increased in depth, with values greater in the CLcr. Despite differences in clay and sand percentages, both soils presented a loamy-clayey texture. The ρb diminished significantly in the uppermost 5 cm of the PD+CR with respect to the UC soils, with values equal to or lower than 1; beyond this depth, the values rose and tended to be equal. The $CaCO_3$ content was greater than 200 g kg^{-1} in both soils, with higher values in VRcc. However, the concentration of this element increased in depth until reaching a maximum of 706 g kg^{-1} in the last depth under the tree canopy in the CLcr. Both soils studied had basic pH values, which were significantly lower at the first two depths of the cover crop.

3.2 SOC, N and C:N

The spreading of the pruning debris and the cleaning residues significantly increased the SOC and N content in both soils, with maximum values in the uppermost 10 cm (Table 4). The differences were significant for depth, location and their interaction. No differences were registered in the SOC and N for each soil type. Under the canopy, both soils presented similar SOC and N contents, with values slightly higher in the upper 5-10 cm.

The C:N ratio reached maximum values in the uppermost 5 cm of PD+CR, being higher than 20 (Table 4). The differences were significant also for the location and type of soil, with higher values in CLcr than in VRcc. Under the canopy and in the last cm of the cover crop, all the C:N values were close to or lower than 10. In all cases, this value diminished in depth.

The percentages of FOM and NFOM are represented in Figure 2. The presence of fresh plant residues increased the FOM in the uppermost cm of the soil; under the canopy and in depth, the FOM decreased.

The addition of debris in PD+CR increased the SOC and N content in the bulk soil, from 26.4 ± 1.2 and 27.1 ± 1.0 Mg C ha^{-1} to 158.0 ± 11.6 and 113.6 ± 17.8 Mg C ha^{-1} in CLcr and VRcc, respectively (Table 5). Under the tree, these values were intermediate for both soils. The stratification was similar in both soil types, higher than 10 for the cover crop and minimum (~1) in conventional tilled soil.

3.3 K^+, CEC and SWC

The CEC and K^+ contents were high for the PD+CR cover of both soils, diminishing over the profile (Table 6). The strongest differences were presented in the first layers of VRcc, with 30 $cmol_c$ kg^{-1} for CEC and K^+ values greater than 2 $cmol_c$ kg^{-1}. The presence of the plant residues on the soil surface also changed the SWC, with values significantly higher in the uppermost 2 or 5 cm of PD+CR and at all depths for the VRcc.

		Texture					
Depth (cm)	Gravel (g kg^{-1})	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	ρb (Mg m^{-3})	$CaCO_3$ (g kg^{-1})	pH (1:2.5)
Chromic Calcisols – Pruning debris + cleaning-residues cover							
0-2	188 (35)	405 (31)	256 (3)	339 (34)	0.9 (0.1)	234 (36)	7.8 (0.1)
2-5	184 (24)	384 (34)	276 (26)	340 (37)	1.0 (0.1)	228 (21)	7.8 (0.1)
5-10	317 (176)	464 (29)	235 (30)	301 (18)	1.7 (0.1)	340 (112)	8.3 (0.2)
10-15	238 (155)	496 (35)	215 (51)	288 (19)	1.8 (0.1)	344 (136)	8.3 (0.2)
15-30	173 (102)	433 (72)	246 (31)	322 (47)	1.7 (0.1)	399 (117)	8.4 (0.2)
Chromic Calcisols – Under canopy							
0-2	147 (94)	458 (59)	203 (52)	339 (30)	1.6 (0.2)	353 (73)	8.3 (0.1)
2-5	167 (97)	480 (41)	181 (28)	339 (18)	1.6 (0.3)	374 (76)	8.3 (0.1)
5-10	160 (49)	483 (25)	184 (23)	333 (14)	1.6 (0.1)	422 (3)	8.3 (0.1)
10-15	163 (124)	500 (9)	177 (84)	322 (28)	1.6 (0.1)	524 (57)	8.3 (0.1)
15-30	276 (104)	521 (40)	201 (28)	278 (16)	1.6 (0.1)	706 (118)	8.4 (0.1)
Calcic Vertisols – Pruning debris + cleaning-residues cover							
0-2	81 (36)	345 (58)	330 (13)	325 (45)	0.9 (0.2)	325 (40)	7.7 (0.1)
2-5	70 (41)	304 (88)	365 (24)	331 (81)	0.9 (0.1)	413 (91)	7.8 (0.1)
5-10	138 (47)	243 (18)	395 (51)	362 (21)	1.3 (0.1)	523 (49)	8.1 (0.1)
10-15	112 (37)	251 (21)	385 (17)	365 (16)	1.4 (0.1)	597 (16)	8.3 (0.1)
15-30	120 (35)	249 (19)	393 (20)	358 (11)	1.4 (0.1)	585 (17)	8.3 (0.1)
Calcic Vertisols – Under canopy							
0-2	87 (17)	225 (13)	407 (15)	368 (3)	1.4 (0.1)	588 (6)	8.3 (0.1)
2-5	56 (11)	226 (7)	401 (15)	372 (17)	1.4 (0.1)	586 (11)	8.4 (0.1)
5-10	64 (39)	231 (25)	400 (14)	369 (14)	1.3 (0.1)	576 (26)	8.4 (0.1)
10-15	85 (18)	250 (59)	407 (28)	344 (34)	1.4 (0.1)	616 (74)	8.4 (0.1)
15-30	115 (105)	304 (53)	393 (45)	302 (14)	1.3 (0.1)	645 (54)	8.4 (0.1)
FACTOR				ANOVA *p*-value			
Depth	0.160	0.349	0.961	0.522	**<0.001**	**<0.001**	**<0.001**
Location	**<0.001**	**<0.001**	**<0.001**	0.822	**<0.001**	**<0.001**	**<0.001**
Soil type	**0.002**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.009**
L x D	0.224	0.115	0.327	0.150	**<0.001**	0.058	**<0.001**
L x S	**<0.001**	**<0.001**	**<0.001**	0.985	**<0.001**	0.166	**0.001**

Table 3. Values for contents in gravel (>2 mm), sand (2-0.05 mm), silt (0.05-0.002 mm) and clay (<0.002 mm); bulk density (ρb); $CaCO_3$, and pH, in each soil type and location at different depths. For each value, the standard error is shown in parenthesis. Factors L: location, D: depth, S: soil type

Depth (cm)	SOC (g kg^{-1})	N (g kg^{-1})	C:N
	Chromic Calcisols – Pruning debris + cleaning-residues cover		
0-2	124.7 (9.0)	5.8 (1.0)	21.8 (3.1)
2-5	122.3 (15.5)	5.6 (1.0)	21.9 (1.3)
5-10	60.0 (13.9)	3.9 (0.5)	15.5 (3.1)
10-15	13.3 (2.1)	1.2 (0.3)	11.7 (3.9)
15-30	9.7 (1.5)	1.2 (0.3)	8.1 (0.9)
	Chromic Calcisols – Under canopy		
0-2	18.3 (10.1)	1.9 (1.0)	9.4 (1.9)
2-5	14.3 (4.9)	1.4 (0.5)	10.0 (0.1)
5-10	14.3 (4.0)	1.5 (0.5)	10.0 (1.8)
10-15	12.0 (1.0)	1.5 (0.5)	8.2 (1.8)
15-30	8.7 (1.2)	1.0 (0.2)	8.7 (0.3)
	Calcic Vertisols – Pruning debris + cleaning-.residues cover		
0-2	118.7 (1.5)	6.2 (0.7)	19.4 (1.9)
2-5	90.7 (0.6)	4.2 (0.9)	22.3 (5.1)
5-10	33.7 (7.6)	2.7 (0.3)	12.4 (1.3)
10-15	14.7 (1.2)	1.9 (0.4)	8.0 (1.2)
15-30	11.7 (2.5)	1.6 (0.2)	7.3 (2.0)
	Calcic Vertisols – Under canopy		
0-2	15.0 (1.0)	2.4 (0.2)	6.2 (0.7)
2-5	15.0 (3.0)	1.9 (0.3)	7.9 (1.9)
5-10	12.7 (3.8)	1.7 (0.6)	7.7 (2.6)
10-15	8.7 (1.5)	1.5 (0.6)	7.1 (4.7)
15-30	6.7 (1.5)	1.1 (0.3)	6.4 (0.9)
FACTOR		ANOVA *p*-value	
Depth	**<0.001**	**<0.001**	**<0.001**
Location	**<0.001**	**<0.001**	**<0.001**
Soil type	0.226	0.101	**<0.001**
L x D	**<0.001**	**<0.001**	**<0.001**
L x S	0.366	0.086	**<0.001**

Table 4. Values of soil organic carbon (SOC), nitrogen (N) concentration, and C:N ratio, in each soil type and location at the different depths. For each value, the standard error is shown in parenthesis. Factors L: location, D: depth, S: soil type

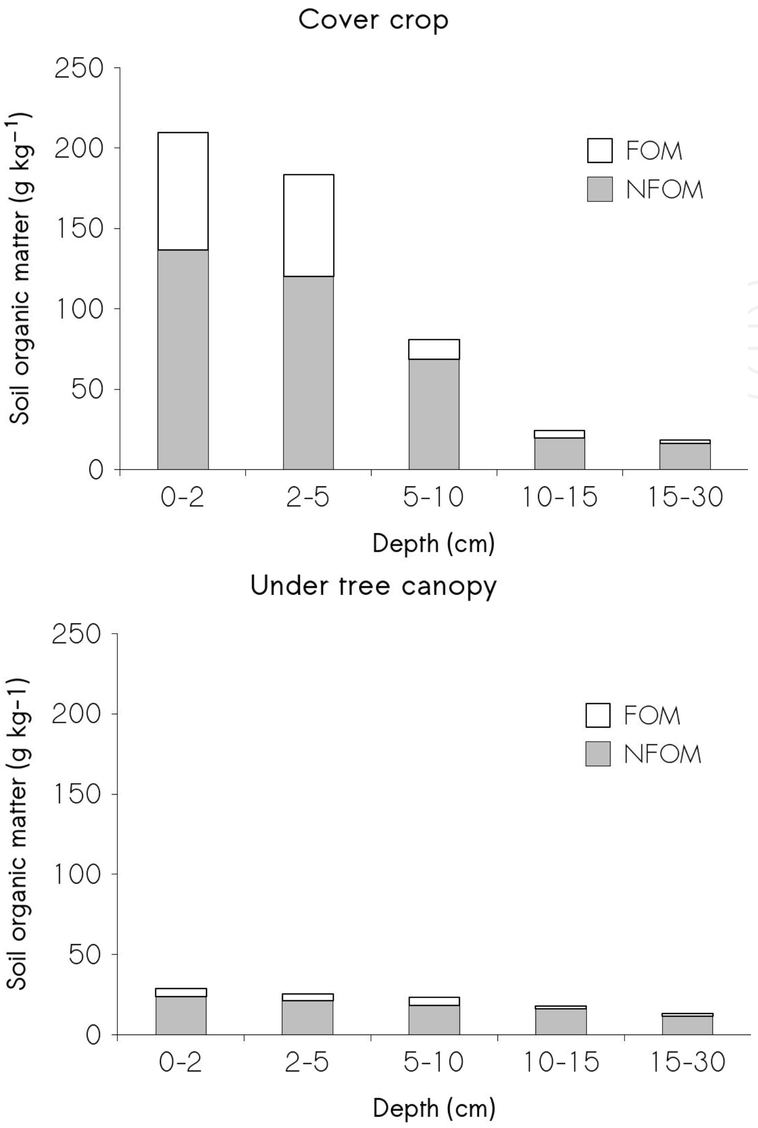

Fig. 2. Contents in floatable (FOM) and non-floatable (NFOM) organic matter in water for each location at the different depths

Soil type		SOC (Mg ha^{-1})	N (Mg ha^{-1})	Stratification ratio of SOC
Chromic Calcisols	Cover crop	158.0 (11.6)a	11.2 (1.1)a	13.1 (1.6)a
	Under canopy	55.4 (11.8)b	6.2 (1.1)b	2.0 (0.9)b
	Tillage	26.4 (1.2)c	3.4 (0.6)c	0.9 (0.1)b
	ANOVA (*p*-value)	**<0.001**	**<0.001**	**<0.001**
Calcic Vertisols	Cover crop	113.6 (17.8)a	10.1 (0.6)a	10.5 (2.2)a
	Under canopy	37.9 (4.5)b	5.4 (2.1)b	2.3 (0.6)b
	Tillage	27.1 (1.0)b	3.8 (0.3)b	1.2 (0.1)b
	ANOVA (*p*-value)	**0.001**	**0.006**	**<0.001**

Table 5. Soil organic carbon (SOC), nitrogen (N), and stratification ratio of SOC for 0-30 cm depth, in each soil type and location. For each value, the standard error is shown in parenthesis

3.4 Correlations with SOC

The correlations between SOC and other soil parameters are summarized in Table 7. The SOC was correlated negatively with the silt content in all cases, and positively with the clay content only in soils without carbon addition (UC). As expected, the SOC correlated negatively with ρb, $CaCO_3$ and pH, and positively with N. The K^+ and CEC correlated

Depth (cm)	K^+ ($cmol_c$ kg^{-1})	CEC ($cmol_c$ kg^{-1})	Soil-water content (m^3 m^{-3}) -33 kPa	-1500 kPa
		Chromic Calcisols – Pruning debris + cleaning-residues cover		
0-2	1.5 (0.8)	22.5 (8.6)	0.34 (0.02)	0.22 (0.01)
2-5	1.5 (0.7)	25.0 (7.0)	0.35 (0.02)	0.25 (0.02)
5-10	1.5 (0.4)	19.6 (3.5)	0.24 (0.03)	0.15 (0.03)
10-15	0.9 (0.4)	17.2 (3.3)	0.17 (0.01)	0.09 (0.01)
15-30	0.6 (0.2)	15.9 (2.2)	0.19 (0.02)	0.11 (0.02)
		Chromic Calcisols – Under canopy		
0-2	1.4 (0.5)	15.1 (0.6)	0.19 (0.04)	0.10 (0.01)
2-5	1.1 (0.5)	17.5 (6.3)	0.17 (0.03)	0.09 (0.01)
5-10	0.8 (0.2)	13.0 (0.6)	0.17 (0.01)	0.10 (0.01)
10-15	0.4 (0.1)	12.0 (1.4)	0.17 (0.01)	0.10 (0.01)
15-30	0.4 (0.1)	10.5 (2.1)	0.17 (0.02)	0.10 (0.01)
		Calcic Vertisols – Pruning debris + cleaning-residues cover		
0-2	2.6 (0.8)	30.0 (7.2)	0.35 (0.03)	0.30 (0.06)
2-5	1.9 (0.5)	25.1 (8.7)	0.31 (0.03)	0.23 (0.05)
5-10	1.3 (0.3)	19.6 (4.8)	0.30 (0.01)	0.18 (0.02)
10-15	0.5 (0.3)	15.9 (2.9)	0.29 (0.02)	0.17 (0.02)
15-30	0.4 (0.1)	15.4 (2.6)	0.29 (0.02)	0.17 (0.02)
		Calcic Vertisols – Under canopy		
0-2	0.8 (0.3)	16.7 (2.9)	0.30 (0.01)	0.18 (0.02)
2-5	0.6 (0.2)	18.0 (1.5)	0.29 (0.01)	0.19 (0.03)
5-10	0.3 (0.1)	16.4 (0.7)	0.29 (0.01)	0.17 (0.02)
10-15	0.2 (0.2)	16.7 (4.8)	0.29 (0.01)	0.17 (0.03)
15-30	0.1 (0.1)	12.5 (2.6)	0.28 (0.02)	0.16 (0.03)
FACTOR		ANOVA *p*-value		
Depth	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Location	**0.008**	**<0.001**	**<0.001**	**<0.001**
Soil type	0.470	**<0.001**	**<0.001**	**<0.001**
L x D	**0.013**	**0.003**	**<0.001**	**<0.001**
L x S	0.053	**<0.001**	**<0.001**	**<0.001**

Table 6. Potassium (K^+), cation-exchange capacity (CEC) and soil-water content at -33 and -1500 kPa in each soil type and location at the different depths. For each value, the standard error is shown in parenthesis. Factors L: location, D: depth, S: soil type

positively with the organic fractions (SOC, NFOM, and FOM), especially in VRcc. Under canopy, the correlation coefficients lowered the significance value, and were not significant for FOM. The correlations between the SWC and the organic fractions were positive and significant in the cover crop of the CLcr; the degree of significance diminishing in the VRcc. No firm correlations were found for the soil fine fraction and SWC.

	All data	CLcr		VRcc	
	(n=60)	PD+CR	UC	PD+CR	UC
			SOC (Mg ha^{-1})		
Silt	-0.94 **	-0.77 **	-0.64 *	-0.68 **	-0.69 **
Clay	0.20	-0.04	0.94 **	0.19	0.89 **
			SOC (%)		
ρb	-0.43 **	-0.82 **	0.07	-0.78 **	0.27
$CaCO_3$	-0.50 **	-0.63 *	-0.36	-0.84 **	-0.44
pH	-0.64 **	-0.80 **	-0.13	-0.90 **	-0.22
N	0.86 **	0.92 **	0.87 **	0.97 **	0.63
K^+	0.80 **	0.58 *	0.65 **	0.94 **	0.77 **
CEC	0.63 **	0.61 *	0.49	0.83 **	0.64 *
SWC -33 kPa	0.53 **	0.84 **	0.61 *	0.64 **	0.04
SWC -1500 kPa	0.56 **	0.86 **	0.51	0.81 **	0.23
			NFOM		
K^+	0.79 **	0.54 *	0.74 **	0.90 **	0.72 **
CEC	0.63 **	0.62 *	0.45	0.80 **	0.70 **
SWC -33 kPa	0.50 **	0.87 **	0.53 *	0.68 **	0.07
SWC -1500 kPa	0.53 **	0.87 **	0.30	0.74 **	0.28
			FOM		
K^+	0.68 **	0.67 **	0.42	0.81 **	0.46
CEC	0.52 **	0.56 *	0.31	0.65 **	0.04
SWC -33 kPa	0.52 **	0.81 **	0.57 *	0.52 *	0.09
SWC -1500 kPa	0.55 **	0.81 **	0.51	0.71 **	-0.17

Table 7. Correlation coefficients of soil organic fractions with the properties studied, for the entire dataset (all data) and for each soil type and location. CLcr: Chromic Calcisols; VRcc: Calcic Vertisols; PD+CR: cover crop with pruning debris and the fruit-cleaning residues; UC: under the tree canopy. * Significant at $P < 0.05$; ** Significant at $P < 0.01$ according to Spearman's test

3.5 RothC

The results for changing soil management from conventional tillage to cover crop are summarized in Table 8. At first, we calculated the annual carbon input for the tillage of olive trees from the SOC concentration measured in neighbouring areas, assuming a steady state. For both soils, the annual input modelled was 1.0 Mg C ha^{-1} yr^{-1}. During the experiment, we measured a carbon input at the soil-surface in PD+CR cover of 23.9 ± 14.3 Mg C ha^{-1} yr^{-1}. After 10 and 6 yr of change in the soil-management system, the annual carbon inputs needed to reach the SOC values between trees as estimated by the model were very similar to those measured in both soils. The turnover time decreased from 26 yr in T soils to 6 and 5 yr for CLcr and VRcc, respectively.

Scenario	Soil type	SOC measured (Mg C ha^{-1})	IOM (Mg C ha^{-1})	Input C modelled (Mg C ha^{-1} yr^{-1})	Input C measured (Mg C ha^{-1} yr^{-1})	Turnover time (yr)
T	CLcr (equ)	26.4	2.0	1.0	-	26
	VRcc (equ)	27.1	2.1	1.0	-	26
PD+CR	CLcr (10 yr)	158.0	2.0	25.3	23.9	6
	VRcc (6 yr)	113.6	2.1	23.6	23.9	5

Table 8. Measured and modelled data for the turnover of organic carbon in olive-grove soils under conventional tillage (T) and mulched with residues from pruning debris and olive-fruit cleaning (PD+CR) (from Nieto et al., 2010)

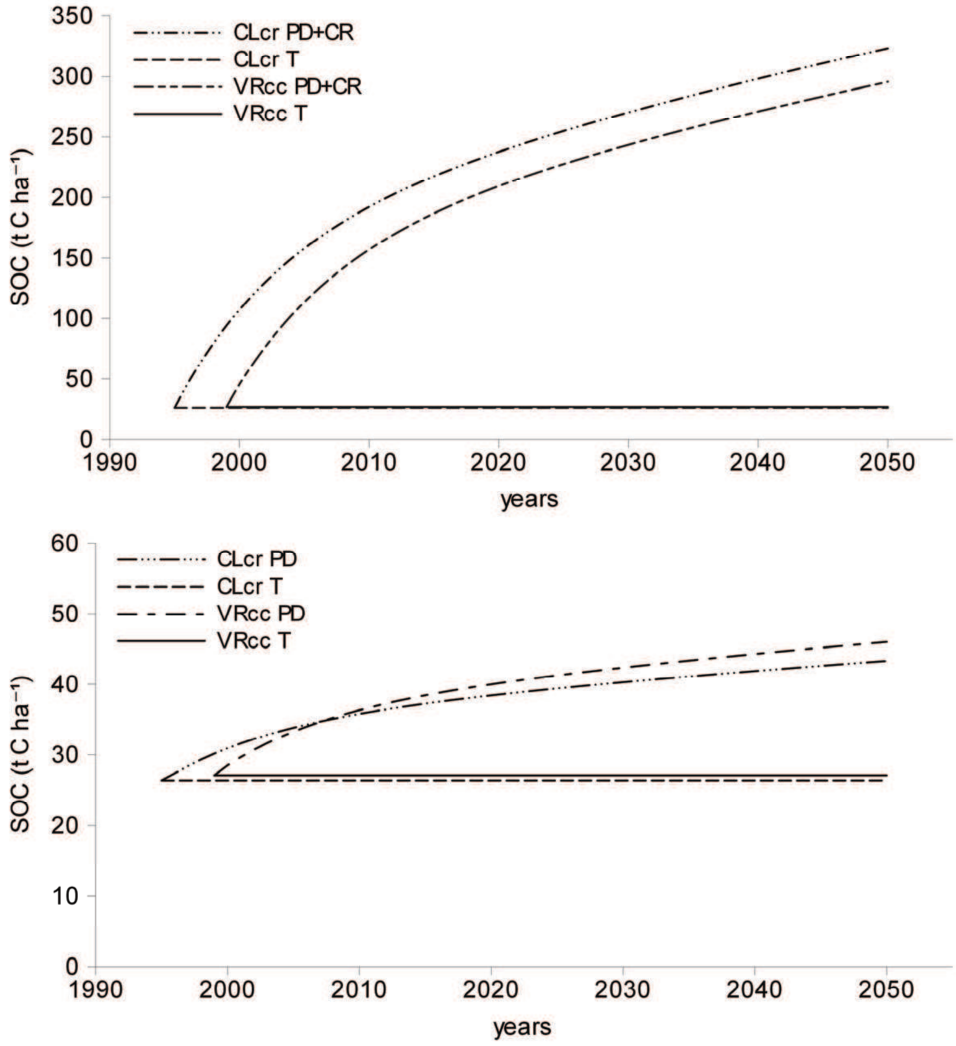

Fig. 3. SOC modelled for CLcr and VRcc under conventional tillage (T), shredded olive-pruning debris cover (PD) and mulching with residues from olive-fruit cleaning and pruning debris (PD+CR) (from Nieto et al., 2010)

The C sequestration was calculated as the difference between CO_2 emissions in each type of management. Under tillage, the cleaning residues were stored in areas close to the oil mill, so that we could not include them in the CO_2 emission balance. Although the pruning debris had a different use in the two cases, under tillage they were burnt and in the cover crop they were spread on the soil.

Figure 3 shows SOC modelled by RothC for 50 yr in both soils under three management systems: cover with PD+CR, only pruning debris (PD), and tillage (Nieto et al., 2010). When mulched with PD+CR the model predicted a continuous increase in SOC, but without reaching a state of equilibrium. No differences could be discerned between either type of soil, due mainly to the large quantities of organic carbon added. When the input was that of PD alone, the model gave a lower SOC content than in the previous case.

CO_2 emissions are given in Table 9 when the PD were burnt in tillage, and when shredded and spread on the ground. As a result of the addition of PD to the soil, the CO_2 that was previously released into the atmosphere during the years of tilled management was reduced more than 55% for both soils. For the decrease in CO_2 emission, the RothC model estimated a potential carbon sequestration of 0.5 and 0.6 Mg C ha^{-1} yr^{-1} for CLcr and VRcc (Table 10). We did not model carbon sequestration after mulching with CRs because this waste matter is normally discarded. Nevertheless, the total carbon content in the soil registered an increase during the experiment of 13.2 and 14.4 Mg C ha^{-1} yr^{-1} for each soil type.

Scenario		CO_2 released to the atmosphere (Mg CO_2 ha^{-1})	
		CLcr (10 yr)	VRcc (6 yr)
Tillage	Burn pruning debris	24.0	14.4
	CO_2 lost from soil	12.0	7.2
	Total	36.0	21.6
Pruning debris	Burn pruning debris	-	-
	CO_2 lost from soil	15.9	9.2
	Total	15.9	9.2

Table 9. CO_2 released into the atmosphere after 10 and 6 years of conventional tillage and mulching with shredded pruning debris, for both types of soil (from Nieto et al., 2010)

Soil type	SOC increase (Mg C ha^{-1} yr^{-1})	CO_2 reduction (Mg CO_2 ha^{-1} yr^{-1})	C sequestration (Mg C ha^{-1} yr^{-1})
CLcr	13.2	2.0	0.5
VRcc	14.4	2.1	0.6

Table 10. SOC increase as result of changes in soil management from conventional tillage to mulching with residues from pruning debris and olive-fruit cleaning (PD+CR). CO_2 reduction and carbon sequestration after the addition of only pruning debris (from Nieto et al., 2010)

4. Discussion

4.1 Soil organic carbon and related soil properties

The two types of soils studied were close together and are widely represented in the areas dedicated to olive cultivation in the Mediterranean region. The parent material, limestone in the CLcr and marls in the VRcc, conditioned the development of different profiles with respect to such characteristics as colour, and content, as well as type of clay, sand, and silt.

Large quantities of soil from nearby zones were applied with the plant residues from olive-fruit cleaning. For this reason, such properties as texture and $CaCO_3$ content presented similar values for the first cm of PD+CR in both soils types. The pH values changed with the SOC content (Thomas et al., 2007).

As opposed to the findings of Fontaine et al. (2004), the addition of fresh organic matter did not cause a negative balance in the SOC, since we began with degraded soils of very low SOC contents. Many authors have also found a rise in SOC values in agricultural soils within at least the uppermost 10 cm in depth, after using conservation practices (Angers et al., 1997; Hernanz et al., 2002; Jarecki & Lal, 2003). In olive orchards, some authors as Hernández et al. (2005), Sofo et al. (2005), Castro et al. (2008) and Gómez et al. (2009), have reported increases in the SOC and N content after applying plant residues. Our values were higher than those reported by these authors because, together with the shredded pruning debris, a major quantity of residues composed of soil and plant debris were brought from the olive-cleaning processes, reaching a biomass accumulation greater than that indicated by these authors. In addition, the soil from the cleaning process originated from the soil under the tree canopy, with small aggregates, fine material and a high SOC content.

Under the tree canopy, despite that the soil was maintained free of weeds with herbicides and free of plant debris by sweeping, SOC values reached 64.7 and 43.3 Mg C ha^{-1}, higher than tilled soils between rows (Table 5). This was due to the greater presence of roots in this zone and the continual dropping of olive leaves, which fell under the canopy, where they remained until the annual cleanup before harvest (Ordóñez et al., 2001; Soria et al., 2005).

The high values of the SOC found in PD+CR indicate the effectiveness of the treatment in terms of storage, reaching values of up to 158.0 Mg ha^{-1} after 10 years of management. These values, together with those of N were far higher than reported by other researchers in agricultural areas (Hernanz et al., 2002; Hernández et al., 2005) but similar to those found by Jarecki & Lal (2005) for forest soils in Ohio.

Texture plays a major role in SOC accumulation in the soil. In many works, the losses of SOC from agricultural soils were lower in clayey soils, since these tended to accumulate this fraction more rapidly and retain it longer (Percival et al., 2000; Arrouays et al., 2006). In our work, a correlation between the SOC and the clay was found only in under the canopy (Table 6), since the input of plant debris changed this relationship. Similar results have been reported by Castro et al. (2008).

According to Hevia et al. (2003) the NFOM presented high correlations with the clay content only in the soils UC (Figure 4). This showed that the addition of plant debris and other residues with high carbon content alter the relation between SOC and the fine-size particle.

The C:N relationship indicates the rate of the mineralization of the soil organic matter. According to Giménez and Bratos (1985), C:N values higher than 15 indicate a very low N release. Our results show high values at the uppermost soil levels of PD+CR, and thus humification processes predominated. At greater depths and in UC, mineralization processes predominating (values lower than 10). It bears mentioning that a high C:N relationship does not necessarily signify N deficiencies in soil, as pointed out by Rhoton et al. (1993), as the progressive increase in organic matter of the soil augments the availability of many nutrients, including N. In this case, the high superficial values cause SOC to act as a protector and store of N, releasing this nutrient little by little into the soil.

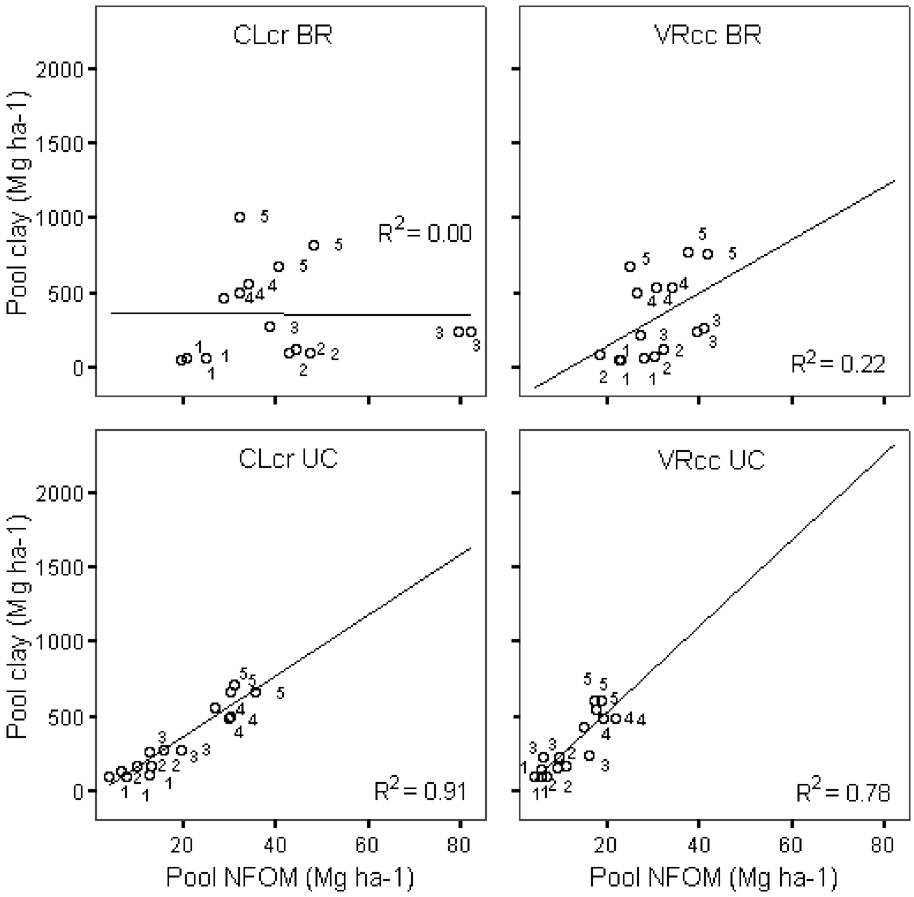

Fig. 4. Linear regression between clay and NFOM (non-floatable organic matter) for each soil type and location (1: 0-2 cm, 2: 2-5 cm, 3: 5-10 cm, 4: 10-15 cm, 5: 15-30 cm)

One of the most important characteristics of this management is the continued non-tillage, which affects the distribution of certain properties such as SOC throughout the soil profile. Franzluebbers (2002) showed that SOC stratification ratios higher than 2 are infrequent under degradation conditions. The data compiled in our study, lower than 2 in conventional tillage and higher in PD+CR cover, confirm the increase in soil quality as well as a control of erosion and degradation processes.

The high values of ρb UC indicated a compaction process related to cultivation (Soria et al., 2005). Between rows, the spreading of olive-pruning debris and the maintenance of the material on the surface (non-tillage) generated a mulching effect (Bescansa, 2006; Lal, 2008) that protected the soil effectively with respect to nutrient loss and sediment production (Rodríguez-Lizana et al., 2008). Thus, ρb diminished in the uppermost 2 cm of PD+CR by

44% in CLcr and by 31% in VRcc, with respect to UC. This difference between the two soil types is related to the SOC content, determined by the application time of the plant residues. Similar results have been reported by Ordóñez et al. (2001) after 6 years of applying olive-pruning debris.

The K^+ content raised with the SOC (Rhoton et al., 1993; Thomas et al., 2007) by 3.4-fold in the VRcc and by 1.5-fold in the CLcr over the entire depth studied with respect to UC. This higher increase observed in the VRcc was linked to the greater content in smectite clays (Bhonsle et al., 1992; Ghosh & Singh, 2001).

According to Oorts et al. (2003) organic matter can be responsible for as much as 85% of the CEC of the soil. The correlation between CEC and SOC found in the present work (Table 6) was similar to those documented by Caravaca et al. (1999) for calcareous soils. The higher values of CEC were detected in VRcc, with lower duration of the experiment and greater fine-fraction content than CLcr (Table 3). These results coincide with those of Leinweber et al. (1993), who indicated that the order of factors that affect the CEC is: particle size of the fraction, management, and duration of the experiment.

The water-storage capacity of the soil changed too with the organic matter content since the pore size and distribution changes (Rawls et al., 2003; Bescansa et al., 2006). However, the effect of SOC on water retention was high in sandy soils and marginal in fine-textured soils (Bauer & Black, 1981). Our results match those of Rawls et al. (2003) in the regression tree for the SWC at -33 and -1500 kPa and in the variation of the moisture with the change in organic-carbon content, which, for high SOC contents, increased for all the textures but in a higher proportion with greater sand contents, as occurred in our case in the CLcr.

4.2 Soil carbon sequestration

The effectiveness of changing the management from traditional tillage to cover crop between trees is manifest in this study in the resulting high SOC and N values. The SOC rose from 34.0 and 46.2 Mg ha^{-1} to 158.0 and 113.6 Mg ha^{-1} for CLcr and VRcc, respectively, indicating greater in soil fertility.

The RothC model estimated the carbon input into the soil of the tilled olive grove in equilibrium as being 1.0 Mg C ha^{-1} yr^{-1}, which falls within the range of 1-2 Mg C ha^{-1} yr^{-1} estimated by Jenkinson & Rayner (1977). Romanyà et al. (2000) registered similar results for a vineyard in the Mediterranean area, with an annual carbon input of 1.4 Mg C ha^{-1} yr^{-1}. The only estimates of carbon input for olive groves were reported by Sofo et al. (2005), who registered an annual input as senescent leaves of 0.4 Mg C ha^{-1} yr^{-1} but did not account for other inputs such as root turnover and rhizodeposition.

In our work, the SOC content modelled for the VRcc soil (Figure 3) was higher than that predicted for the CLcr after eight years of mulching. This might be explained by the higher percentage of clay in the VRcc soil, which is masked by the large quantities of organic matter added in the form of PD+CR. The relationships between fine soil fractions and organic-carbon sequestration have been addressed by other authors such as Paustian et al. (2000). It has been noted that carbon is physically protected against biodegradation when it is contained in clay- or silt-sized micro-aggregates (Balesdent et al., 2000).

The RothC model fitted carbon turnover satisfactorily for the change from tillage to PD+CR cover due to the absence of erosion (Gottschalk et al., 2010). During the 10 and 6 years that the experiment lasted, we registered a much higher annual input of residues into the soil between trees than that reported by other authors, due to the fact that our management system included the addition of cleaning residues as well as pruning debris. For this scenario, RothC predicts an annual input of 25.3 and 23.6 Mg C ha^{-1} yr^{-1} for CLcr and VRcc soils, respectively (Table 8), thus confirming that the model closely fits this kind of management.

Turnover time is defined as the migration of organic carbon through a given volume of soil (Jenkinson & Rayner, 1977). The high values found in tillage (Table 8) indicate carbon stabilization in the soil, signifying that carbon migrates slowly from one pool to another. Our results are higher than those modelled for Kenyan savanna (~16 yr) or dry forest in Zambia (~8 yr) by Jenkinson et al. (1999). For PD+CR the turnover times were lower than those found by these latter authors. This showed rapid migration of carbon and thus a soil that is not close to equilibrium.

During the first years of olive-tree establishment, CO_2 is distributed preferentially in the permanent structures and the root system, but in mature olives trees, fixed CO_2 is located to a greater extent in the leaves and fruit, and consequently also in the pruning debris (Sofo et al., 2005). Thus pruning debris is an important carbon reservoir that can be returned to the soil rather than the atmosphere in the form of CO_2 (Figure 3). When the pruning debris is shredded and spread on the ground, the RothC model predicts a decrease in CO_2 emission of ~2 Mg CO_2 ha^{-1} yr^{-1} for each soil (Table 10). This value is within the range of the data collected by Smith et al. (2008) for warm-dry zones, who registered an emission reduction of 3.45 Mg CO_2 ha^{-1} yr^{-1} when degraded lands are restored and 0.33 Mg CO_2 ha^{-1} yr^{-1} for croplands under tillage and residue management.

Abandoning tillage in favour of using organic waste to cover the ground is considered to be an efficient way of increasing carbon sequestration in agricultural soils (cf. Smith et al., 2008; Lal, 2008). In our experiment, we measured a carbon sequestration of 0.5 and 0.6 Mg C ha^{-1} yr^{-1} with pruning debris cover in CLcr and VRcc soils, respectively (Table 10). Fairly wide ranges have been estimated for carbon sequestration in agricultural soils. Álvaro-Fuentes et al. (2009) measured a carbon sequestration of 0.46 and 0.15 Mg C ha^{-1} yr^{-1} for continuous barley and barley-fallow rotation in Mediterranean area, respectively. For the European area, Smith et al. (2000) estimated a carbon sequestration of 0.7 Mg C ha^{-1} yr^{-1} with crop residues and 0.4 Mg C ha^{-1} yr^{-1} with no tillage. Using organic residues Hutchinson et al. (2007) registered average rates of potential carbon gain from 0.1 to 0.5 Mg C ha^{-1} yr^{-1}. After changes in cropland use, and introduction of the best series of management techniques for every land use and climate zone, IPCC (2000) suggested a carbon sequestration potential of 0.3 Mg C ha^{-1} yr^{-1}. Our results coincide with these values, supporting the idea that the recycling of pruning debris in olive groves is an effective way of storing carbon in the soil. As with SOC, carbon sequestration was greater in VRcc soil, with its higher clay content.

Apart from the carbon sequestration from the recycling of pruning debris, the addition of the fruit-cleaning residues and the absence of tilling resulted in an increase in SOC (Figure 3). Although it may be difficult to introduce the reuse of the large quantities of CR + PD described in this work as a commonplace practice in olive-grove management, merely recycling the pruning, which is produced in the grove itself, together with a policy of zero tillage, will increase the SOC content considerably compared to T soils.

5. Conclusions

This work shows the improvement in soil quality and fertility after the soil management in olive orchards was changed from conventional tillage to non-tillage with plant residues cover. The application of shredded olive-pruning debris and the plant residues and soil from olive-fruit cleaning increased the organic fraction in both soils, CLcr and VRcc, with respect the tillage soils. The changes affected the uppermost 10 cm of the soils although the SOC content was greater in the CLcr, where the management spanned a longer time period.

With the change in SOC, some soil properties were affected. The spreading of plant residues lowered the pH and the ρb in the uppermost soil depths between trees, where there was an effect of mulching with respect to under canopy soils, and the N content increased. The slow release of this N ensured plant nutrition and the soil fertility despite the high values of the C:N relationship.

The non-tillage generated a highly fertile surface layer in PD+CR, which also protected the soil physically, as demonstrated by the high stratification observed, similar to that described in forest systems. In addition, the NFOM percentage, although higher under the tree canopy, was high in both types of soils, indicating the stability of the material applied. The addition of plant debris also increased the K^+ content, CEC and water-storage capacity, improving the soil quality.

When the soil management was changed from conventional tillage to cover crop with PD+CR, carbon storage in the soil improved considerably together with its general quality. Carbon turnover in Mediterranean olive-grove with PD+CR cover was quite accurately predicted by the RothC model. Over the long term, the carbon sequestration was higher in soils with greater quantities of clay. A soil-management system that abandons tillage in favour of reusing both pruning debris and the residue from cleaning the olives to cover the ground, constitutes the most effective way of increasing soil quality and diminishing CO_2 emissions in one of the most extensive agricultural enterprises in the entire Mediterranean area.

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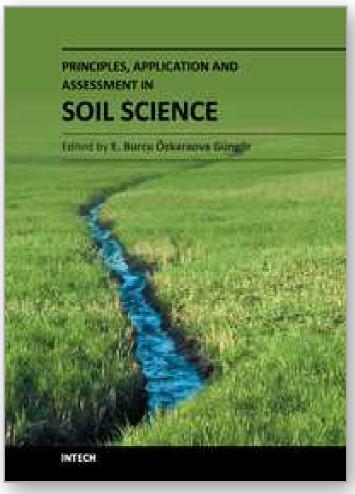

Principles, Application and Assessment in Soil Science
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Our dependence on soil, and our curiosity about it, is leading to the investigation of changes within soil processes. Furthermore, the diversity and dynamics of soil are enabling new discoveries and insights, which help us to understand the variations in soil processes. Consequently, this permits us to take the necessary measures for soil protection, thus promoting soil health. This book aims to provide an up-to-date account of the current state of knowledge in recent practices and assessments in soil science. Moreover, it presents a comprehensive evaluation of the effect of residue/waste application on soil properties and, further, on the mechanism of plant adaptation and plant growth. Interesting examples of simulation using various models dealing with carbon sequestration, ecosystem respiration, and soil landscape, etc. are demonstrated. The book also includes chapters on the analysis of areal data and geostatistics using different assessment methods. More recent developments in analytical techniques used to obtain answers to the various physical mechanisms, chemical, and biological processes in soil are also present.

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