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Opportunities of super high-density olive orchard to improve soil quality: Management guidelines for application of pruning residues

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ABSTRACT

Applying pruning residues in the lanes of olive groves has become a popular practice because it is economical and accrues benefits for soil and water management. This study presents an analysis of the impact of different rates of pruning residue on soil properties, in particular related with soil quality. Over 4 annual campaigns, chopped pruning residues used as a mulch were analyzed in terms of composition, coverage and moisture content to evaluate their effects on the amount of soil organic carbon (−10 cm and −20 cm) and CO_2 emissions, temperature and moisture. The experiment was carried out in a super-intensive olive orchard in Cordoba (SE, Spain) and used four amounts of fresh pruning residue: 7.5 t ha^{-1}(T1), 15.0 t ha^{-1} (T2) and 30.0 t ha^{-1} (T3), with a control T0 = 0.0 t ha^{1}.

Mulch mean leaf fraction was 46.0 ± 17.5% (±SD) and initial water content, 24.8 ± 8.6%. The mulching benefits for soil moisture were observed in amounts of pruning residue >7.5 t ha^{-1}, which are only produced in super-intensive olive groves or in orchards with high tree densities. The low impact of the treatments on soil moisture was explained by the dramatic annual variations in residue moisture contents, caused by the regimes of high temperatures and rainfall-evapotranspiration deficits inherent to the Mediterranean Basin climate. Thus, the mulching capacity only resulted efficient when the residues were still humid in spring. In addition, 15.0 t ha^{-1} of pruning residues was the threshold to provide significant increases in soil organic carbon at depths of 0–20 cm. Thus, accumulating pruning residue in lanes at rates of over 15 t ha^{-1} (T2 and T3) is more convenient than a uniform distribution with lower amounts, due to the low mineralization rates occurring during warm seasons and the larger inputs of OM increasing the annual balance of SOC.

1. Introduction

Agricultural soils are acquiring increasing relevance due to the effects of water conservation management systems to improve “C-sequestration” (Hepburn et al., 2019). It is crucial to identify the most suitable management practices adapted to the features of the different agroecosystems, and to quantify their impact, in order to support guidelines maximizing soil carbon stocks (FAO, 2017).

The case of olive groves is significant because they have played a major role in the culture of the Mediterranean Basin for at least the last three thousand years (Rallo et al., 2013; Gómez et al., 2014). Currently, olive trees occupy 1% of agricultural soil worldwide (Vilar and Pereira, 2017). In Spain, olive trees cover an area of 2,7 Mha, of which over 60% is situated in Andalusia, the southernmost region of Spain (Spanish Ministry of Agriculture, Fisheries and Food, 2019). Soil conservation and C sequestration are urgent topics associated with innovative management strategies, because olive orchards have traditionally been cultivated on hilly areas with high erosive energy and low cover protection (e.g. Gómez-Limón et al., 2012). Currently, different types of cover crops are being used to reduce erosion risk and to promote soil carbon conservation (Nieto et al., 2012; Márquez-García et al., 2013).

Olive farming has recently undergone a dynamic evolution in techniques in response to new socioeconomic conditions. High and super high-density (SHD) olive orchards, designed for mechanized harvesting,

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are spreading in flatter, more productive locations with good water availability. In traditional olive farming, tree density ranges from 17 to 150 trees ha^{-1}, mainly in proportion to the annual rainfall, whereas in the new, intensive SHD orchards, which are irrigated and mechanized, the density varies from 400 to as many as 2000 trees ha^{-1}, respectively (Rallo et al., 2013). SHD systems, also known as hedgerow olive orchards (with an average of 700–2000 trees ha^{-1}) are gaining popularity worldwide mainly due to their rapid mechanized harvesting and pruning, high crop levels and early bearing. These features make SHD systems profitable, and they are therefore commonly chosen for new plantations, especially in non-traditional olive-growing countries, such as Argentina, Australia and the USA (Diez et al., 2016). Nowadays, although there are no official numbers for the extension of SHD olive systems, agricultural unions estimate they may cover more than 500, 000 ha worldwide, and their popularity is on the rise.

Despite the fact that low vigor cultivars are used in SHD plantations, they produce large amounts of pruning residues, due to the relatively higher position of the branches with respect to the main trunk. Traditionally, pruning residues have been burnt, either to reduce the risk of accidental fires or to prevent the transmission of pests and diseases such as *Phloeotribus scarabeoides* Bern and *Verticillium* wilt, respectively. Given the high cost of this traditional practice, the use of chopped pruning residues in the lanes of olive groves is becoming a common practice in Andalusia (Calatrava and Franco, 2011). This mulching technique provides an opportunity to improve soil functioning. In fact, chopped pruning residues have been described as an effective water and soil conservation measure, reducing erosion, preserving soil moisture, decreasing the appearance of weeds and the application of herbicides, as well as contributing to the improvement in fertility and C sequestration (Bound, 2014; Rodríguez-Lizana at al., 2008, 2017; Xiloyannis et al., 2008; Calatrava and Franco, 2011; Repullo-Ruiberriz de Torres et al., 2018; Gómez-Muñoz et al., 2016; Prosdocimi et al., 2016; Henry et al., 2018). Particularly, the incorporation of organic matter coming from the higher rates of pruning residues from SHD olive orchards could significantly improve soil functioning and contribute to mitigating the effects of global climate change.

However, water and soil conservation measures show difficulties in selecting and allocating best management practice adapted to the space-time hydrological variability of the environment, the scale and crop type (e. g. Correa et al., 2018; Uribe et al., 2018). In the case of pruning residues and their subproducts, there is still a clear need to explore the long-term effects (e.g. Gómez-Muñoz et al., 2016). The efficiency of pruning residue applications is usually measured by indicators such as dry weight and the fraction of ground cover (Jiménez-Jiménez et al., 2013), with the latter particularly relevant for erosion control. However, to the best of our knowledge, no long-term studies have attempted to determine the thresholds of olive tree pruning residue levels leading to significant improvements in soil functioning, particularly regarding organic carbon dynamics and the physical parameters involved, such as soil moisture and temperature. To assess the impact of the maintenance of different levels of pruning residues on the orchard soil, it is crucial to optimize its application and to improve soil properties and water retention. On the other hand, it is also advisable to explore the risk associated to accidental fires during the summer due to high temperatures recorded, which promoted the traditional burning of pruning residues.

The general objective of this study is to analyze the impact of the application of different rates of pruning residues on soil properties. To do so, we evaluated rates of pruning residues ranging between 0 and 30 t ha^{-1} distributed as mulch strips during four crop seasons in a standard SHD olive orchard, as follows: 1) the pruning residues from a standard SHD olive orchard were characterized in terms of initial compositions, and percentages of moisture and ground cover; 2) the seasonal effects of the different rates of mulching on soil temperature and moisture were evaluated at different soil depths; and 3) the impact of the residue rate on the amount of organic carbon was evaluated at different depths and in different periods along with the seasonal patterns of CO_2 emissions.

2. Material and methods

2.1. Study site

The study area is located at Campus de Rabanales, University of Cordoba (SE Spain), in a total land area of 260 ha located 7 km from the city of Cordoba (37.9° N, −5.4° W). It is characterized by an altitude ranging between 114 and 173 m and a mean slope of 1%. The annual average rainfall is ca. 600 mm, with an average daily temperature of 17.3 °C and a variation range between 28.2 °C in July and 9.0 C° in January. The soil types are inceptisols, alfisols and vertisols, associated with the geological unit of *Terrazas del Guadalquivir* (Campillo-García et al., 1993).

The trial was carried out in an experimental SHD olive orchard planted in 2011 with the cultivar 'Arbequina'. The distances between rows and trees within rows were 7 and 2 m, respectively. The experimental area comprised 7 tree rows with 15 trees per row (length of ca. 30 m) and their corresponding five inter-row lines (Fig. 1). The most relevant initial soil properties described for the first 20 cm depth of soil were the following: clay loam texture (clay% = 27.5; sand% = 40.4; silt % = 32.1); CIC (meq/100g) = 24.1; oxidizable organic matter content% = 2.5; organic N% = 0.17; pH (ClK) = 7.4; P (Olsen) (mg.kg-^{1}) = 8.0; K (mg.kg-^{1}) = 296.

Four treatments corresponding to different loads of fresh pruning residues were evaluated: T0 = control, bare ground; T1 = 7.5 t ha^{-1}; T2 = 15.0 t ha^{-1} and T3 = 30.0 t ha^{-1}. These amounts were selected because they represented the average pruning waste produced by a standard rainfed SHD olive orchard (T1) and a SHD irrigated orchard (T2). For T3, we doubled the amount of T2 because it is already common practice among olive growers to apply the pruning residues of two consecutive tree-rows in alternate lanes. Moreover, the lesser T1 amounts can be also linked to extensive olive groves. The experiment followed a complete randomized block design with five replicates, where each experimental unit consisted of a 2 × 6 m (12 m^2) plot between tree rows, with a total of 20 experimental units, where the four treatments (T0, T1, T2 & T3) were randomly assigned. Fig. 1 illustrates the experimental design and the distribution of the experimental units and the treatments within each block.

Climatological features and the availability of personnel and machinery determined the pruning dates every year. The pruning residues were processed with a knife chopper in February 2016 and 2017 for the first and the second campaigns; March 2018 for the third and at the beginning of April 2019 for the fourth. To set up the experiment, the lanes were first cleaned and swept, then, the experimental units were set up in the lanes and the treatments randomized. The same agronomical management was applied to the trial as to the surrounding olive orchard. This management consisted roughly of: watering with 2000 m^3 ha^{-1} applied by drip irrigation from May to September; treatment with herbicide (glyphosate, 4.5 l ha^{-1}) using a tractor mounted boom sprayer in April, July and October; weed control with brush cutter and harvesting with a straddle harvester between January and March, depending on the rainfall distribution.

2.2. Pruning residue analyses: composition, cover fraction and moisture percentage range

The composition of the pruning residues was measured at the beginning of the four campaigns after the residues were chopped and ground. To do so, we analyzed samples (200 g; n = 10) composed of mixed material taken proportionally from the different lanes, which were then dried at 70 °C in an oven until they reached a constant dry weight (ca. 48 h). The percentages of dry weight of leaves, twigs (diameter less than 0.8 cm) and wood (branches) were calculated. Additionally, we measured the initial moisture content (IMC) of the

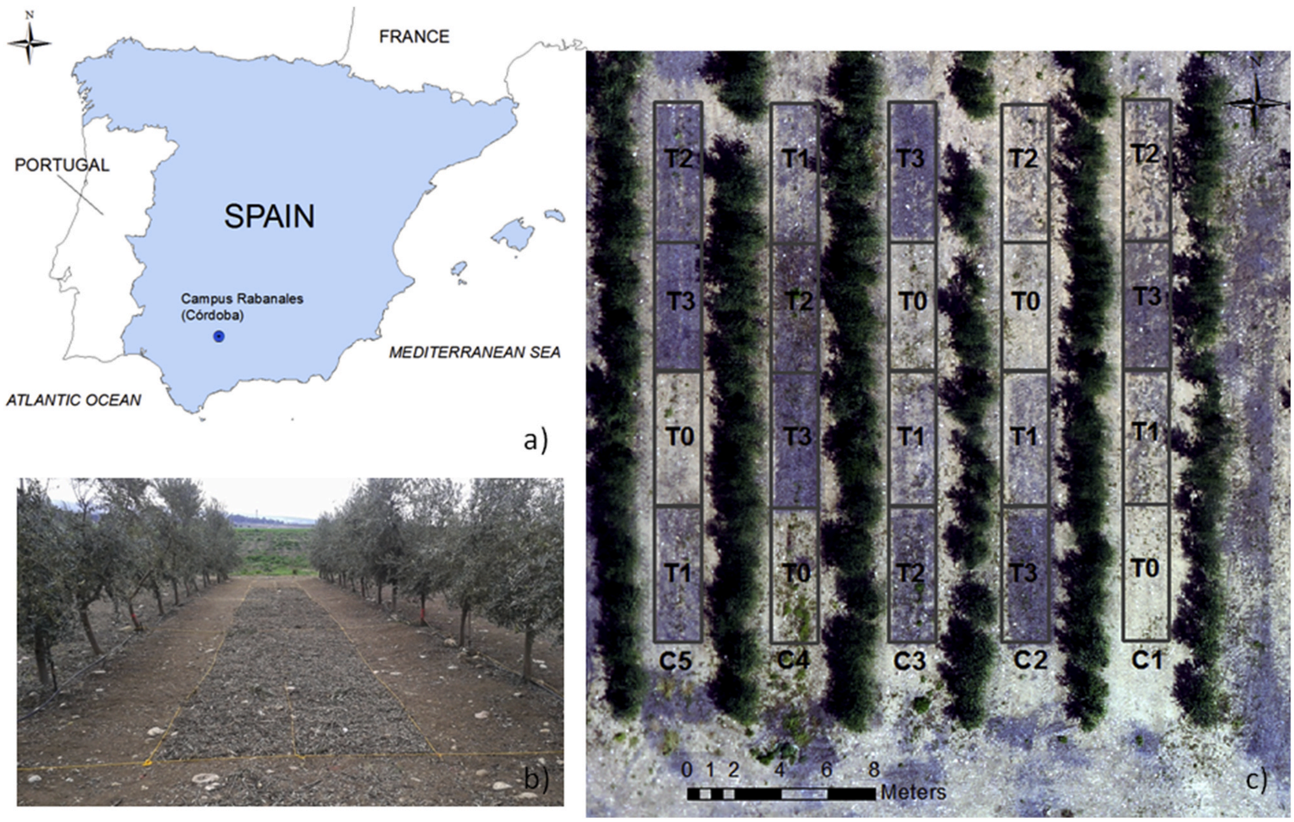

Fig. 1. Location and details of the study plots: a) situation; b) picture of one of the lanes; c) aerial orthophography with 5 blocks and 4 treatments. (C = lane, with numerical code; T0 = control, bare soil; T1 = treatment with residue rate of 7.5 t ha^{-1}; T2 treatment with residue rate of 15.0 t ha^{-1} and T3 treatment with a residue rate of 30.0 t ha^{-1}).

residues every campaign following the same sampling procedure (n = 20; approximate weight = 75 g). The sampling dates were 18-Feb-2016; 22-Feb-2017; 21-Mar-2018 and 3-Apr-2019 (Table 1).

To observe its maximum variation interval, moisture changes of pruning residues were monitored during the first campaign every 30 and 45 days, depending on the precipitation regime observed (n = 8, see Table 1).

Finally, at the beginning of the first and second campaigns (March-16 and March-17), the fraction of the surface area covered by pruning residues (% coverage) was calculated from photographs taken at a height of 4 m from a camera attached to a telescopic rod. The pictures were reconstructed and georeferenced in ARCGIS 10 (ESRI, 2016). A mesh of 0.5 × 0.5 m step (n = 48 per plot) was used to measure the fraction of cover with a quantitative graphic pattern used to count the pixels of the covered soil. Finally, the average percentage of surface coverage corresponding to each treatment (n = 5) was calculated.

2.3. Soil properties

2.3.1. Soil moisture

Soil moisture at a depth of between 0 and -10 cm (SM_0) was measured over the four campaigns (22 surveys). Additionally, soil moisture at a depth of −10 to −20 cm (SM_{10}) was also measured during the second, third and fourth campaigns (13 surveys). In each survey, a series of cylindrical samples of approximately 125 cm^3 were taken from approximately the same lane position in each plot (n = 20; 5 samples per treatment). The samples were dried at 105 °C to produce a constant dry weight (ca. 24 h). The sampling dates were selected to quantify the changes associated with the variations in the climatological conditions or the impact of the management operations (see dates and distribution in Table 1).

A three-way Analysis of Variance (ANOVA) was performed to explore the effects of seasonal features, rates of mulching (treatments) and depths on soil moisture content over the year. The significance tests of the random effects were carried out by calculating the F statistics and the p-value (significance) levels for each effect (seasonal, treatment and depths). The assumptions of normality and homoscedasticity were explored and the comparative graphs of the mean values were also produced to interpret the differences in the climatological context of the year. The statistical treatment of the data was performed using STATISTICA 8.0 (StatSoft, 2007).

2.3.2. Surface and subsurface temperatures

A series of punctual temperature measurements in the surface plot were taken with a thermographic camera (Flir E60; Wilsonville, Oregon, United States) with sensitivity below 0.05 °C using non-refrigerated micro bolometer technology, recording images with a size of 320 × 240 pixels. The temperature measurements were taken in 23 surveys over 4 campaigns (see Table 1) between 9.00 and 11.00 a.m.

Afterwards, we calculated the spatial mean temperature of each plot ($STemp_0$), evaluating the shaded and sunny areas and weighing at least three measurements from each one (n = 3). In addition, $STemp_0$ was compared with the soil temperature below the residue (URTemp) and with the temperature at a depth of −10 cm ($STemp_{10}$).

A three-way ANOVA was performed to evaluate the effects of seasonal climatological variations (seasons), treatments (T0-T3) and depth ($STemp_0$ and $STemp_{10}$) on the plot surface temperature. A *t*-test was also applied to compare the means of $STemp_0$ and URTemp. Finally, a two-way ANOVA determined the interactions of treatments and seasons on URTemp. The statistics F and p of the analyses were calculated with the STATISTICA 8.0 program (StatSoft, 2007).

Finally, a quadrocopter, model MD4-1000 (Microdrones GmbH, Siegen, Germany), was used as UAV to perform 6 flights with a high resolution uncooled thermal camera Gobi 640 GiGe (Xenics

Table 1
Sample dates of the measurements carried out in each campaign.

Campaign	Sampling dates soil moisture	Sample dates temperature	Sampling Dates SOC	Sampling Dates CO_2 emissions	Sampling dates Composition/IMC
1	18-May-2016	17-May-2016			18-Feb-2016
(Feb-16-Jan-17)	20-May-2016				
	23-May-206				
	25-Jul-2016	25-Jul-2016			
		19-Aug-2016[b]			
		25-Aug-2016[b]			
		30-Aug-2016[b]			
		1-Sep-2016[b]			
		12-Sep-2016[b]			
		14-Sep-2016			
	15-Sep-2016	15-Sep-2016[b]			
	3-Nov-2016	3-Nov-2016	16-Nov-2016		
	20-Dec-2016	20-Dec-2016			
	1-Feb-2017	1-Feb-2017			
2	21-Mar-2017	21-Mar-2017			22-Feb-2017;
(Feb-17-Feb-18)	21-Sep-2017[a]	17-May-2017			
	19-Feb-2018[a]	18-Jul-2017		16-Jun-2017	
		22-Nov-2017	23-Nov-2017[a]		
		22-Dec-2017		2-Dec-2017	
		31-Jan-2018			
3	17-Apr-2018[a]	17-Apr-2018		29-Jan-18	21-Mar-2018
(Mar-18-Mar-19)	16-May-2018[a]	16-May-2018		12-Jun-18	
	13-Jul-2018[a]	13-Jul-2018		25-Jul-18	
	21-Sep-2018[a]	21-Sep-2018			
	29-Nov-2018[a]	29-Nov-2018	3-Dec-2018[a]	30-Nov-2018	
	16-Jan-2019[a]	16-Jan-2019			
4	21-May-2019[a]	21-May-2019		14-Feb-2019,	3-Apr-2019
(Apr-19-Feb-20)	9-Jul-2019[a]	9-Jul-2019		6-Jun-2019,	
	26-Sep-2019[a]	26-Sep-2019			
	4-Dec-2019[a]	4-Dec-2019	28-Nov-2018[a]	3-Dec-2019,	
	29-Jan-2020[a]	29-Jan-2020		21-Jan-2020	

[a] Indicates that measurements were also taken at soil depths of −10 to −20 cm.

[b] Indicates that measurements taken from UAV with thermal camera to evaluate risk of fires.

Headquarters, Lueven, Belgium) of 640 × 480 pixel resolution. The aim was to explore the surface temperatures of plots with different rates of residues for the months of water deficit to evaluate the potential risk of accidental fires that could constraint its use. In Table 1, can be observed the dates of flights taken at HORA with a HEIGHT of m. The thermal images of 20 plots were cut and treated with R-scripts to calculate the values of mean spatial temperatures (T_{s_UAV}) and standard deviation for each treatment and flight. A correlation analysis (correlation coefficients and significance) was carried out to evaluate the weight of rates of residues on the surface temperatures. One-way ANOVA (statistics *F, p* and *df*) was applied to check the influence of treatments and flight dates on T_{s_UAV}.

2.3.3. Soil organic carbon and CO_2 emissions

The impact of the different residue rates on the soil carbon balance was studied with measurements of soil organic carbon (SOC) at depths from 0 to 10 cm (SOC_0) and 10–20 cm (SOC_{10}). For SOC_0, four samples were taken in total (1 per campaign, n = 4), while only three were taken for SOC_{10}, in campaigns 2, 3 and 4 (Table 1, n = 3). The SOC was determined by the procedure described by Anderson and Ingram (1993), based on colorimetry after oxidation with a mixture of potassium dichromate and sulfuric acid. The impact of depth, treatment and time "under treatment" was evaluated for SOC. SOC_0 and SOC_{10} were checked separately because the size sample was different (4 and 3, respectively). One-way ANOVA tests (statistics p, df and F-Senedecor) were applied to explore the effects of the treatment and time on SOC_0 and SOC_{10}. The impact of depth only was examined on the values corresponding to campaigns 2–4. Moreover, scatterplots for SOC-treatment-time were depicted to show the tendencies and the relationships found. The multiple linear regressions were adjusted with the coefficients of determination and significance.

In addition, soil respiration measurements (CO_2 emissions) were performed for each plot. These required PVC pipes (inner diameter = 105 mm), which were installed one week before the measurements were taken. An opaque CO_2 flow chamber (Model 6400–09) coupled to an infrared gas meter (IRGA) model Li-6400xt (Li-COR, Lincoln, NE, USA) was used. Ten surveys were carried out over campaigns 2, 3 and 4 (Table 1, n = 10), so that the measurements were representative of the daily averages. To avoid daytime fluctuations, the measurements were taken between 10.00 a.m. and 2.00 p.m. (local time, GTM+1; Larionova et al., 1989; Davidson et al., 1998; Xu and Qi, 2001; Almagro et al., 2009). The basic statistics of CO_2 emissions were calculated, and two-way ANOVA was applied to examine the effects of treatment and seasonal variations. Pearson's correlation coefficients and scatterplots were also used to evaluate their potential relations with soil moisture and temperature measured on similar dates (<15 days' difference).

2.4. Climatological features of the campaigns

Precipitation, average daily temperature and evapotranspiration values were taken from the IAS-CSIC agrometeorological station of UCO-B.G.Olivo (Rabanales–Córdoba; http://www.uco.es/grupos/meteo), located on the farm. Table 2 summarizes the monthly statistics of the daily average temperature (AvT), accumulated precipitation (AcP) and potential evapotranspiration (AcET), while Fig. 2a compares the seasonal values of these variables. As observed in Table 2, despite the variability within campaigns, similar temperature statistics were recorded among campaigns. The highest mean value for this variable was 18.9 °C, obtained in campaign 4, while the minimum was 17.1 °C, in campaign 3. The maximum and minimum variation intervals were recorded for spring (17.4–20.6 °C) and autumn (15.2–16.1 °C), respectively. Finally, the summer season was extremely hot (Fig. 2) with

Table 2
Summary of the monthly statistics of daily average temperature (Av_T_d, °C), accumulated precipitation (Ac P, mm) and reference evapotranspiration (Ac ET_0, mm). (Month Av = monthly average; St.Dv = standard deviation; Min = minimum; Max = maximum; Accum = accumulated).

Campaigns (1–4)	Sta.	Av_T_d (°C)	Ac P (mm)	Ac ET_0 (mm)
1-Feb-16-Jan-17 (n = 12 months)	Month Av	18.7	62.6	102.6
	St.Dv	8.1	53.7	67.4
	Min	7.7	9.5	28.2
	Max	30.8	169.7	213.0
	Accum		751.3	1231.6
2-Feb-17-Feb-18 (n = 13 months)	Month Av	17.9	41.0	109.0
	St.Dv	7.9	27.6	69.6
	Min	8.3	0.0	30.0
	Max	28.8	81.2	218.8
	Accum		533.3	1416.9
3-Mar-18-Mar-19 (n = 13 months)	Month Av	17.1	62.7	102.4
	St.Dv	7.0	87.9	64.9
	Min	7.9	0.0	30.7
	Max	29.5	314.3	219.2
	Acum		815.1	1330.6
4-Apr-19-Feb-20 (n = 11 months)	Month Av	18.9	42.5	130.4
	St.Dv	6.8	67.1	70.8
	Min	9.0	0.0	4.5
	Max	28.4	218.7	220.1
	Accum		467.5	1434.7

maximum daily temperatures over 40 °C (c.f. series maximum of 45.9 °C collected on 9-Jul-16) and temperatures below 0 °C were recorded in winter, as expected in Mediterranean climates.

In the case of AcP, there were notable differences in terms of range and distribution, as can be observed in Table 2. The highest AcP was 815 mm for campaign 3 and the lowest was 468 mm, in campaign 4. The average monthly precipitation also showed high variability, with an interval between 41.0 and 62.7 mm (campaigns 2 and 3, respectively; Table 2). The monthly maximum and minimum values of precipitation were from 0.0 (Sep-17; Jul-18, May-19; Jun-19, Jul-19) to 314.3 mm (Mar-18), respectively. In contrast, the AcET patterns were fairly similar for all campaigns, with similar monthly and seasonal values (Table 2 and Fig. 2). The maximum seasonal ET was collected in summer (over 550 mm) and the minimum in winter (less than 150 mm) for all campaigns (Fig. 2a). The AcET ranged from 1231.6 mm to 1434.7 mm (campaigns 1, Fig. 2a and b) and 4, respectively). Campaign 4 presented the highest annual water deficit (with a value of 967 mm; Table 2). Apart from the expected differences between accumulated precipitation and evapotranspiration which are typical from Mediterranean regimes, it is important to highlight how water deficits greater than 250 mm were observed in spring for campaigns 2, 3 and 4 (Fig. 2).

3. Results

3.1. Pruning residue analyses: composition and initial moisture content and cover

The initial compositions (in dry weight %, IMC) for all the campaigns are shown in Fig. 3. A wide variability was observed among samples with coefficients of variations greater than 30%. The most evident differences were observed in campaigns 2 and 3, when leaf fraction ranged from 69.7% (±11.5%) to 27.7% (±7.7), respectively, whereas branches ranged from 15.8 (±7.7%) to 48.9% (±11.3; Fig. 3a). No appreciable correlations were observed between the percentage by dry weight of the different fractions (DWL, DWT and DWB) and the IMC of the sample residue ($r<0.35$; $p>0.05$; Fig. 2a). The IMC values were close to 30% for all campaigns while in 4, a very dry winter and spring (Fig. 2a) and the delayed date of pruning operations and collection (April) led to a mean value of 12%. Fig. 2b shows the variations of residue moisture during campaign 1. It is worth highlighting the increase of water content in seasons with higher precipitation than evapotranspiration as well as the clear reduction of moisture (<10%) in spring and summer. The residue moisture varied during campaign 1 between 3.7% (4-May-16) and 39.3% (20-Dec-16; Fig. 2b). This notable reduction in water content (in terms of mass and volume of residue) in spring could lead to mulches with a lower capacity for insulation of the soil surface.

Fig. 3b presents the correlations between the averaged fraction of ground cover (%) for campaigns 1 and 2 and the rate of fresh residue (t. ha^{-1}) of each treatment. For campaign 1, T0 presented an averaged cover of 7.3% (±2.5), 41.3% (±5.1) for T1, 58.2% (±11.7) for T2 and 88.3% (±5.8) for T3 (n = 5 per treatment). For campaign 2, with similar values of initial moisture and a notably higher abundance of leaves - the cover fraction was slightly greater (8.0% ± 0.4 for T0, 44.1% ± 2.5 for T1,

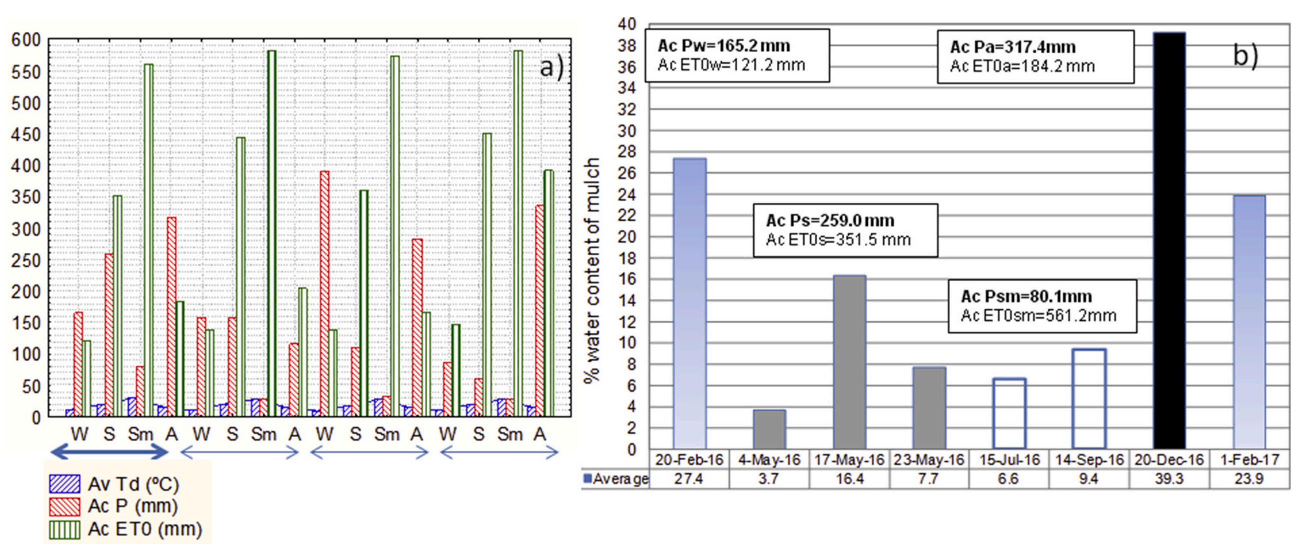

Fig. 2. Values of accumulated potential evapotranspiration (Ac. ET0), precipitation (Ac. P), mean daily temperatures (Td) and residue water content (average % of the sample): a) seasonal values for the four campaigns (W = winter, S = spring; Sm = summer; A = autumn); b) For campaign 1, the percentage of water content in pruning residue samples with collection dates. In addition, seasonal accumulated values of potential evapotranspiration, precipitation and mean temperatures are shown.

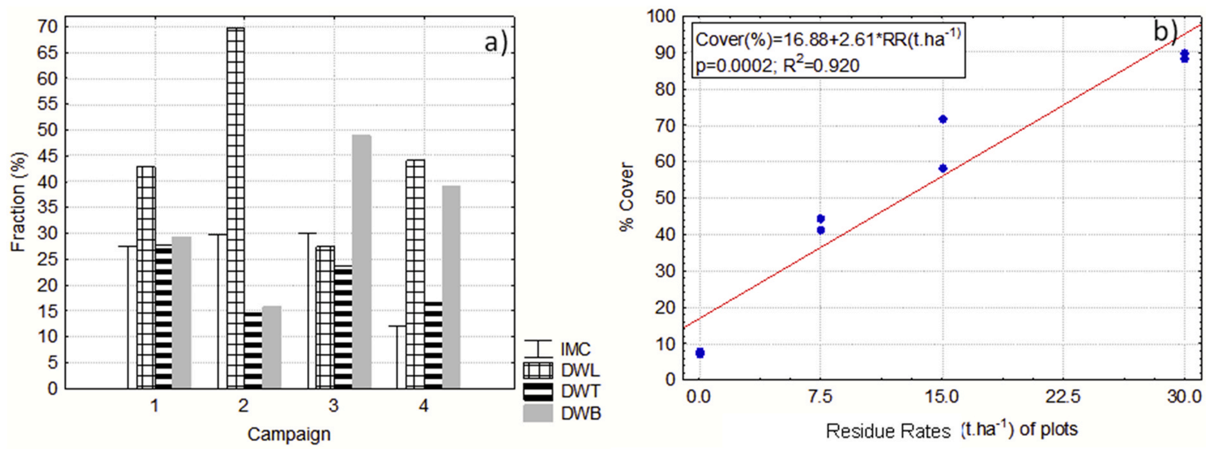

Fig. 3. Initial Values of water content, composition and ground cover of pruning residues for the four campaigns: a) IMD = initial water content (%), DWL = dry weight of leaves, DWT = dry weight of twigs, DWB = dry weight of branches; b) relation of residue rates (RR, t.ha^{-1}) with initial ground cover (%) for campaigns 1 and 2.

71.8 ± 1.0 for T2 and 89.8 ± 7.0% for T3). In Fig. 3b, the adjustment of mean fraction cover and residue rate is shown with only eight points to explore different scenarios based on the abundance of residues ($p > 0.05$, $R^2 = 0.92$).

3.2. Soil properties: moisture and temperature

3.2.1. Soil moisture: treatment, depth and season effects

Regarding the seasonal average soil moisture, T0 showed the lowest value at 0–10 cm depth (Fig. 4a; SM_{0_W} = 15.6%; SM_{0_Sp} = 11.9%; SM_{0_Sm} = 6.5%; %; SM_{0_Sm} = 13.8%) whereas T3 (SM_{0_W} = 17.5%; SM_{0_Sp} = 16.9%; SM_{0_Sm} = 7.1%; %; SM_{0_Sm} = 15.8%) obtained the highest percentage, with the exception of the summer mean value, when T1 was slightly greater (SM_{0_Sm} = 7.5%). Moreover, there were significant correlations between the residue rates (treatments) and $SM_{0,}$ except for the summer seasons, when the differences among the campaigns were less than 1%. Remarkably, SM_0 values were very close for T1 and T2 during the year, while T3 proved the most efficient treatment for water conservation in spring (>5% compared to T0).

In the case of SM_{10}, only during the winter, a significant correlation between residue rates and SM_{10} was observed. Moreover, narrower variation intervals of SM_{10} (Fig. 4a and b; $SM_{10\_W\_T0}$ = 15.4% and $SM_{10\_W\_T3}$ = 17.2%; $SM_{10\_Sp\_T0}$ = 12.1% and $SM_{10\_sp\_T3}$ = 13.7%) and lower differences among treatments (<2%) than SM_0's were found.

ANOVA showed the significant effects of the treatment (F = 3.080; df = 3; p = 0.027, Table 3) and season (F = 125.601; df = 3; p = 0.000, Table 3) and the lack of effects of depth and the interactions of treatment, season and depth (p > 0.05, Table 3).

3.2.2. Surface and subsurface temperatures

3.2.2.1. Surface and subsurface punctual temperature measurements: effects of treatment, depth and season. Significant seasonal differences in $STemp_0$ and $STemp_{10}$ were observed using ANOVA (effect of season, F = 183.341, df = 3, p = 0.000; effect of season x depth, F = 4.912, df = 3, p = 0.002; Fig. 5a and b and Table 3). The rest of the factor interactions

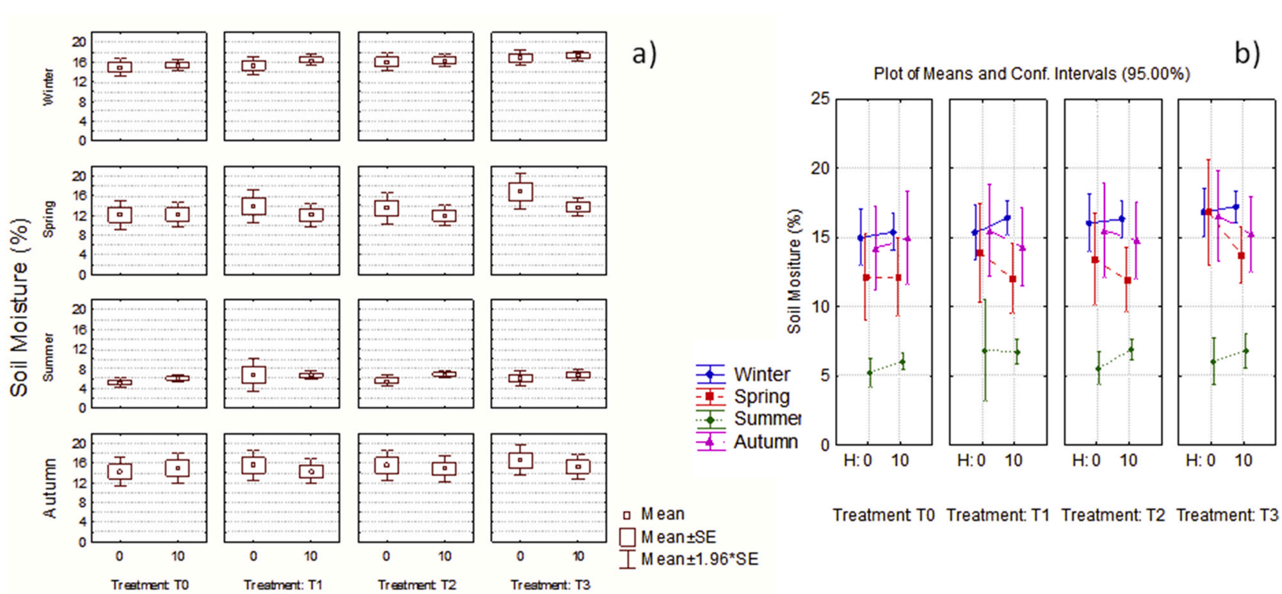

Fig. 4. Seasonal distribution of soil moisture for the different treatments and depths: a) box and whiskers diagrams of soil moisture content (%) for the different seasons and treatments (T0 = control, bare soil; T1 = treatment with a residue rate of 7.5 t ha^{-1}; T2 treatment with a residue rate of 15.0 t ha^{-1} and T3 treatment with a residue rate of 30.0 t ha^{-1}; 0 = soil depth between 0 and 10 cm, SM_0; 10 = soil depth between 10 and 20 cm. SM_{10}; SE = standard error); b) Interactions of soil depth, treatment and season on soil moisture.

Table 3
Summary of statistic tests applied for exploring effects of treatment, season depth and “time under treatment with variance analyses (F statistics, degree of freedom and significance are presented) on the study variables.

Property	Test	Treatment	Depth	Season	Time	Interactions
Soil moisture	Three-way ANOVA	F = 3.080; df = 3; **p = 0.027**	$p > 0.05$	F = 125.601; df = 3; **p = 0.000**	–	$p > 0.05$
Soil temperature	Three-way ANOVA	$p > 0.05$	$p > 0.05$ *URTemp ($p < 0.05$)	F = 183.341, df = 3, **p = 0.000**	–	“Season x Depth” (F = 4.912, df = 3, **p = 0.002**), the rest $p > 0.05$
Soil surface temperature (UAV-summer)	One-way ANOVA	$p > 0.05$			F = 185.698; df = 5; **p = 0.000** (flight dates)	–
SOC_0	One-way ANOVA	F = 9.039, df = 12, **p = 0.002**	–	–	$p > 0.05$	–
SOC_{10}	One-way ANOVA	F = 5.575, df = 8, **p = 0.023**	F = 6.876, df = 22, **p = 0.016** (*campaign 2–4 only)	–	$p > 0.05$	–
CO_2 emissions	Two-way ANOVA	$p > 0.05$	–	F = 58.670, df = 3, **p = 0.000**	–	Season x treatment “F = 3.69, df = 9, **p = 0.000**

presented $p > 0.05$.

It is worth noting how $STemp_0$ was not correlated with the residue rates, with the exception of the mean value observed in winter for surface temperature ($STemp_{0w\_T0} = 10.8$ °C and $STemp_{0w\_T3} = 11.9$ °C; Fig. 5b). In summer, the difference of $STemp_{0Sm}$ for the treatments was the lowest of the year (only 0.5 °C difference), while the maximum was observed in spring when the impact of the mulch was more evident (1.8 °C difference). On the other hand, $STemp_{10}$ presented narrower variation intervals and a different pattern with the minimum difference among treatments for the winter (0.3 °C) and the maximum for the summer (0.9 °C; Fig. 5a). Despite the fact that mean temperatures $STemp_0$ and $STemp_{10}$ showed a difference greater than 1 °C, they were not significant ($p = 0.120$), as occurred in the case of treatments ($p = 0.940$). For $STemp_0$, T0 always presented the lowest values compared with the treatments with residues, while very similar $STemp_{10}$ values were obtained independently on the presence of residues and percentage

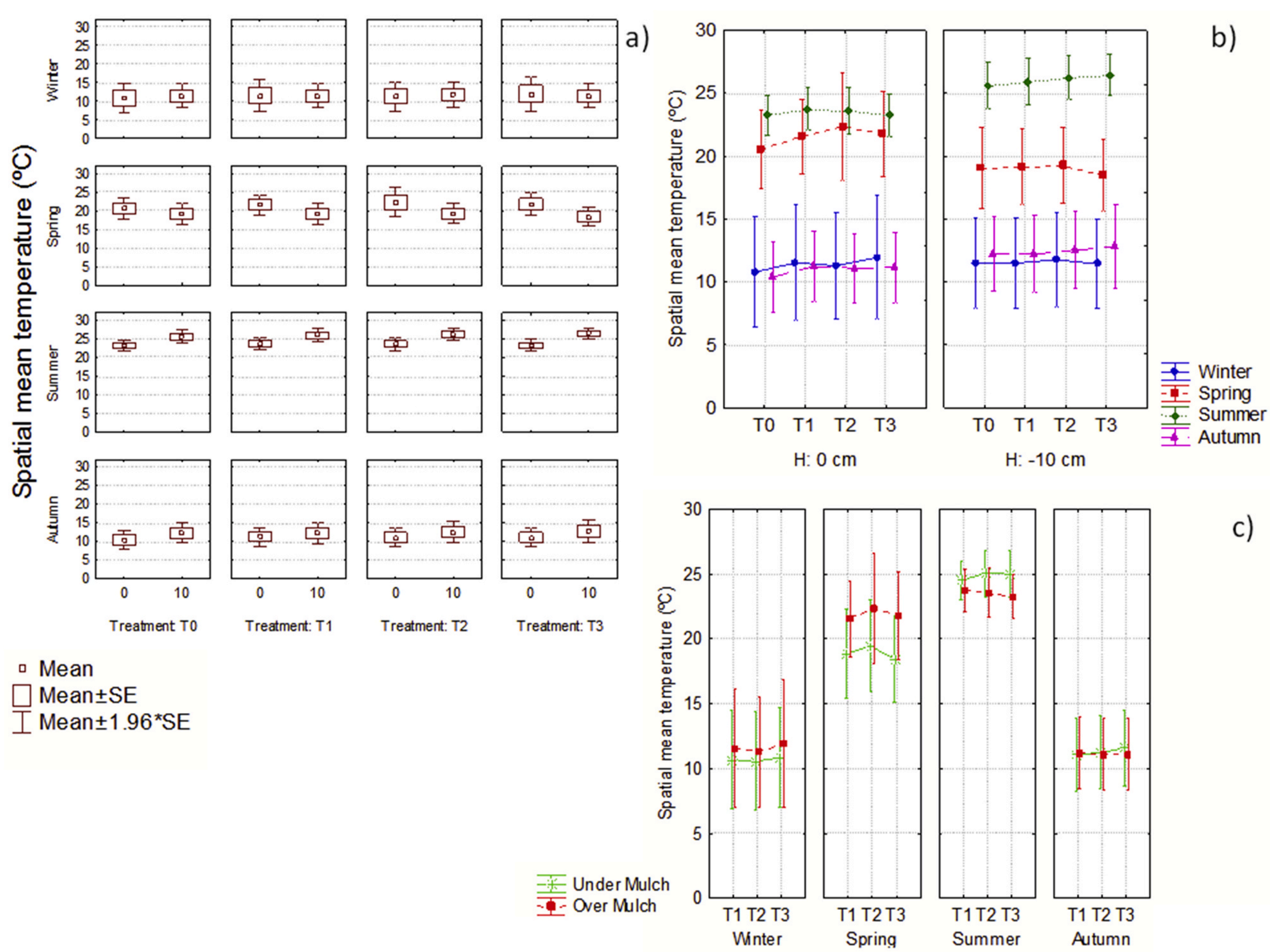

Fig. 5. Seasonal spatial mean temperature for the different treatments and depths: a) box and whiskers diagrams of spatial mean temperature, $STemp_0$ and $STemp_{10}$, for the different seasons and treatments (T0 = control, bare soil; T1 = treatment with a residue rate of 7.5 t ha^{-1}; T2 treatment with a residue rate of 15.0 t ha^{-1} and T3 treatment with a residue rate of 30.0 t ha^{-1}; 0 = surface measurement, $STemp_0$; 10 = soil depth at 10 cm, $STemp_{10}$; SE = standard error); b) Interactions of depth, treatment and season on spatial mean temperature; c) Seasonal spatial mean temperatures over mulch ($STemp_0$) and under mulch (URTemp) for the different seasons and treatments T1, T2 and T3.

of shaded areas.

Finally, URTemp was not significantly different (p = 0.970) from $STemp_0$ (Fig. 5c) in spite of the differences between the temperatures of the residue and soil in spring (which varied over 2.7 °C for T1 and 3.3 °C for T3). The surface of the residue was warmer than the soil in winter and spring, whereas in summer this pattern changed. In autumn, URTemp and $STemp_0$ were very similar.

3.2.2.2. Surface temperatures from thermal images during summer. The effect of treatment on T_{s_UAV} was not significant (p > 0.05; Table 3). The range of variation was between 45.3 °C (T1) and 47.6 °C (T3); T_{s_UAV} for bare soil (T0) was equal to 46.1 °C. There was not significant correlation of the T_{s_UAV} of the plots of each flight with the rates of residues (r = 0.10, p > 0.05; n = 120). On the other hand, T_{s_UAV} for the different flights were between 38.2 °C (12-Sep-2016) and 56 °C(15-Sep-2016; Table 4) and were significantly distinct (F = 185.698; df = 5; p = 0.000; Table 3). The total mean T_{s_UAV} reached 46.5 °C with a standard deviation of 7 °C.

3.2.3. Soil organic carbon and CO_2 emissions

Fig. 6a) shows the values of SOC_0 for the campaigns evaluated. Interestingly, for campaign 1, SOC_0 ranged between 1.34% (T0) and 1.85% (T3), for campaign 3, between 1.08% (T0) and 2.04% (T3), and for campaign 4 between 1.12% (T0) and 2.59% (T3). Only for campaign 2, significant rates of mineralization were quantified for treatments T0 and T1 with the lowest values of SOC_0 close to 1.15%. In addition, there was a significant correlation between the residue rates and SOC_0-values, except for campaign 2 (Fig. 6a). ANOVA analyses showed the only significant differences associated to the treatment (F = 9.039, df = 12, p = 0.002; Table 3) while "time under treatment" presented p > 0.05. In fact, similar relationships (SOC_0-time under treatment) were found for T0 and T1. In contrast, the impact of T2 and T3 over the campaigns was especially evident. In particular, T2 presented a significant linear correlation, where the longer the treatment, the more organic carbon was stored ($T2\_SOC_0(\%) = 1.36 + 0.02.t$ (months); p = 0.01). The mean increases of SOC_0 for each treatment were −0.56 mg g^{-1} soil for T0, 0.44 mg g^{-1} soil for T1, 2.92 mg g^{-1} soil for T2 and 2.86 mg g^{-1} soil for T3.

Although SOC_{10}_T3 presented the highest values and the impact of the treatment derived from ANOVA resulted significant (F = 5.575, df = 8, p = 0.023; Table 3), there was no strong correlation between the residue rates and SOC_{10} for T1 and T2, which were very close (Fig. 6c and d). ANOVA analysis also showed a lack of significant effects of "Time under treatment" on SOC_{10} (p > 0.05; Table 3), which is illustrated by the weak correlations shown in Fig. 6b–d.

Finally, the effects of depth evaluated from ANOVA were significant (F = 6.876, df = 22, p = 0.016; Table 3). As can be observed in Fig. 6a–c, the interval variations for 10-20 cm-depth were notably lower and narrower than the corresponding to 0-10-cm-depth, with values between 0.81% (T0) and 1.36% (T3) in campaign 2, 0.96% (T0) - 1.55% (T3) and 1.01% (T0) - 2.14% (T3) for campaign 3 (Fig. 6c).

In the case of CO_2 emissions, there were significant differences among the seasonal patterns (F = 58.670, df = 3, p = 0.000; Fig. 7a and Table 3) and seasonal x treatment (F = 3.69, df = 9, p = 0.000; Fig. 7b and Table 3) but there were no significant effects linked to the treatment (p > 0.05). T2 and T3 showed the narrowest variation intervals over the year (Fig. 7b). A positive correlation of respiration and residue rates (T2 and T3) was observed for winter and autumn, and a negative one in spring and summer (where T0 presented the maximum value). In seasonal terms, the narrowest variation interval was recorded in winter, with mean values ranging between 1.61 μmol $CO_2.m^2.s^{-1}$ (T1) and 2.06 μmol $CO_2.m^2.s^{-1}$ (T2), while the maximum range occurred in autumn, when T0 presented 1.41 μmol $CO_2.m^2.s^{-1}$ and T2, 3.96 μmol $CO_2.m^2.s^{-1}$. For spring and summer, T0 presented the maximum values of respiration of 4.10 μmol $CO_2.m^2.s^{-1}$ and 3.49 μmol $CO_2.m^2.s^{-1}$, respectively (Fig. 7b).

In Fig. 7c, the relations between respiration and SM_0 and $STemp_0$ for similar dates indicated a positive and weak correlation with the temperature (r = 0.41; p < 0.05) and a negative one with the soil moisture (r = −0.42; p < 0.05). Both variables were unable to explain the seasonal variations of CO_2 emissions.

4. Discussion

Numerous authors have described and/or quantified the benefits on soil water conservation of different types of mulches such as straw, composted sludge, plastic, etc (e.g. Ismaili et al., 2015; Valdecantos et al., 2014; Gao et al., 2017) as well as its relevance on erosion control (Jordán et al., 2010; Prosdocimi et al., 2016; Cerdà et al., 2018; Li et al., 2020, among others). However, a minor number of papers have been addressed to mulching applications of olive pruning residues. The main outcomes of our experiment were the following:

- Despite the variability of the AcP and its seasonal pattern over the four years, soil moisture and surface temperatures were relatively stable, likely as result of a lower deviation in AcET and mean temperatures, and because the soil type (clay loam) conserves the water content efficiently. The effect of the different accumulated precipitation (Table 2) can be also evaluated in the moisture contents of the pruning residues (see IMC values in Fig. 3a), which had very similar values, around 30%, in the first three campaigns. In contrast, when pruning residues were collected later, as happened in the fourth campaign, (April), there was a notable reduction (up to 12%) likely as a result of the dramatic increase of spring evapotranspiration. Authors such as Chaubey et al. (2010), Valdecantos et al. (2014), Pan et al. (2018) and Uribe et al. (2020), among others, have described the impact of precipitation regimes and water deficits on the efficiency and behavior of sustainable management practices in different agricultural crops and land-uses.
- As for the composition of pruning residues, it is significant how campaigns 1 and 4 had similar DWL, DWT and DWB fractions, while showing very different moisture contents. In contrast, campaigns 1, 2 and 3 presented very similar IMC, despite the differences in the fraction of leaves measured for campaign 2 (of approximately 70%; Fig. 2a). As mentioned above, environmental variables such as mean temperature and evapotranspiration should play a relevant role in justifying the differences among IMCs. However, these differences between fractions of leaves, twigs and branches must have also influenced the degree of ground cover. In fact, the higher percentages of leaves in campaign 2 could explain the small variations observed in Fig. 3b, thus relating cover fraction and the rate of fresh residue. It is relevant to note that 7.5 t ha^{-1} meant an average coverage of approximately 40%. Jiménez-Jiménez et al. (2013) found a ground cover value of 41.3% for a residue rate of 10.2 t ha^{-1}, and 60.2 for a treatment with 20.4 t ha^{-1}, when a similar method of

Table 4

Statistics (mean, standard deviation and coefficient of variation) of the thermal images of plots taken for the UAV flights grouped by treatments and flight dates. (T = rates of fresh pruning residue; 7.5 t ha^{-1}(T1), 15.0 t ha^{-1} (T2) and 30.0 t ha^{-1} (T3), with a control T0 = bare soil).

Basic sta.	n	Mean (°C)	St. Dv (°C)	CV(%)
Total	120	46.5	7.0	15.0
19-Aug-2016	20	52.3	2.5	4.7
25-Aug-2016	20	39.0	1.3	3.3
30-Aug-2016	20	44.6	2.4	5.5
1-Sep-2016	20	38.2	1.2	3.2
12-Sep-2016	20	56.0	3.0	5.4
15-Sep-2016	20	48.6	2.9	6.1
T0	30	46.1	7.0	15.3
T1	30	45.3	6.7	14.9
T2	30	46.9	7.3	15.5
T3	30	47.6	6.9	14.5

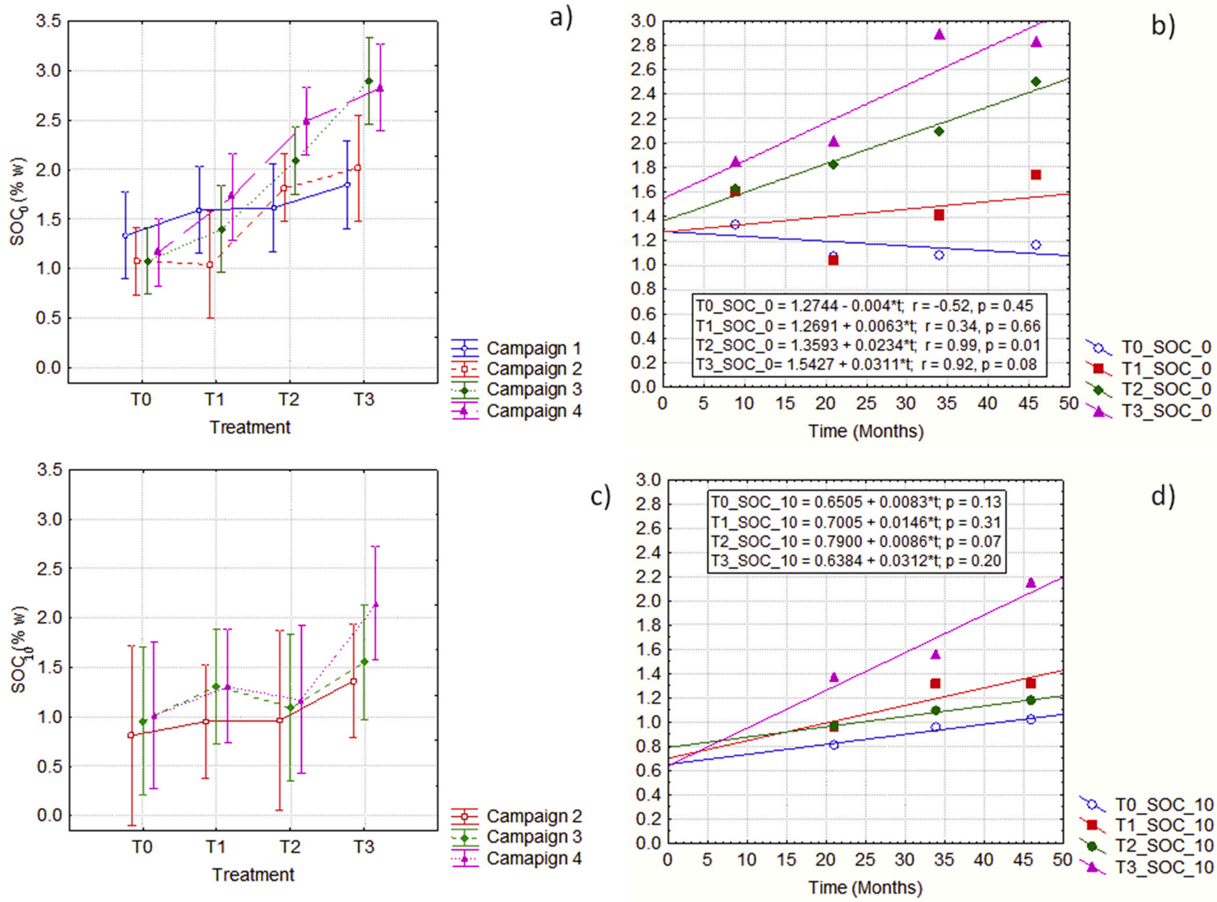

Fig. 6. Characterization of soil organic carbon (SOC) for the different depths, treatments and time under treatment: a) Interactions between campaigns and treatment on the values of SOC at the depth between 0 and 10 cm (SOC_0; T0 = control, bare soil; T1 = treatment with a residue rate of 7.5 t ha^{-1}; T2 treatment with a residue rate of 15.0 t ha^{-1} and T3 treatment with a residue rate of 30.0 t ha^{-1}; 0 = surface measurement, $STemp_0$; 10 = soil depth at 10 cm, $STemp_{10}$; SE = standard error); b) Scatterplots of SOC_0 and number of months with residues. The linear regression adjustments were included with the correlation coefficient, *r*, and the significance, *p*; c) a) Interactions between campaigns and treatment on the values of SOC at the depth between 10 and 20 cm (SOC_{10}); d) Scatterplots of SOC_{10} and number of months with residues.

evaluation was applied. Both values were well-correlated with the adjustment of Fig. 3b. These high-pruning residue yields can only be associated with super-intensive olive groves, and therefore, much lower ground cover values would be expected (and applied every two years) in commercial extensive and intensive olive groves (with lower densities).

- The low impact of the treatment on soil moisture over the year, and particularly in summer, can be explained by taking into account the intra-annual variations of residue moisture (Figs. 2b–4b). The interaction of soil and mulch temperatures with precipitation, and more clearly, with evapotranspiration, must control the insulating effects of mulching on the soil. Thus, only in spring, when the residues are still humid and fresher, can the residues contribute notably to preserving the soil moisture content. On the other hand, this season is critical for fruit formation. This was particularly clear for the treatment with 30 t ha^{-1}, and similar patterns were produced for 7.5 and 15 t ha^{-1}. Pan et al. (2018) highlighted that soil and water conservation benefits did not always increase with higher application rates of chipped branches residues, where other factors -such as soil surface coverage, interception by mulching, soil permeability, stability of mulching materials, and rill initiation-could be also relevant.
- The effect of the residue rates on the mean surface temperature of the plots was not significant and had no effect on soil depth. The weight of the location in the hillslopes, the aspect and the shaded areas associated to row canopies of trees (see graphical abstract) can explain the differences compared to Mahdavi et al. (2017) with straw mulch in grass crops or to those of Taguas et al. (2019), who underscored the significant impact of the shaded area and the residue rates on the point measurement of temperatures. Warmer temperatures were not only linked to higher residue rates (T2 and T3; Table 4) but to sunnier areas also. Thus, variations in the sun's position over the year, which are responsible for the different shaded fractions in the plots, meant that the mean spatial temperatures were not well-correlated with residue rates (treatment). The amount of residue did not have an impact on the soil temperatures under and over the residues. Apparently, the temperature below the residues was higher than that above them, which highlighted again the loss of mulching capacity when high values of temperature and evapotranspiration are recorded. These results can disagree with the experiments carried out in labor/and with rainfall simulator to evaluate runoff generation and water dynamics associated to storm events. For instance, Montenegro et al. (2013) observed a significant lower soil temperature with wheat straw application rates of 4 t ha^{-1} than with application rates of 2 t ha^{-1} and under bare soil.
- As far as soil organic carbon is concerned, the threshold of 15 t ha^{-1} of pruning residues provided a notable increase in organic carbon over the different campaigns at both depths studied. Thus, it would be advisable to concentrate the pruning residues in only some of the lanes (e.g. alternate lanes). Authors such as Gómez-Muñoz et al.

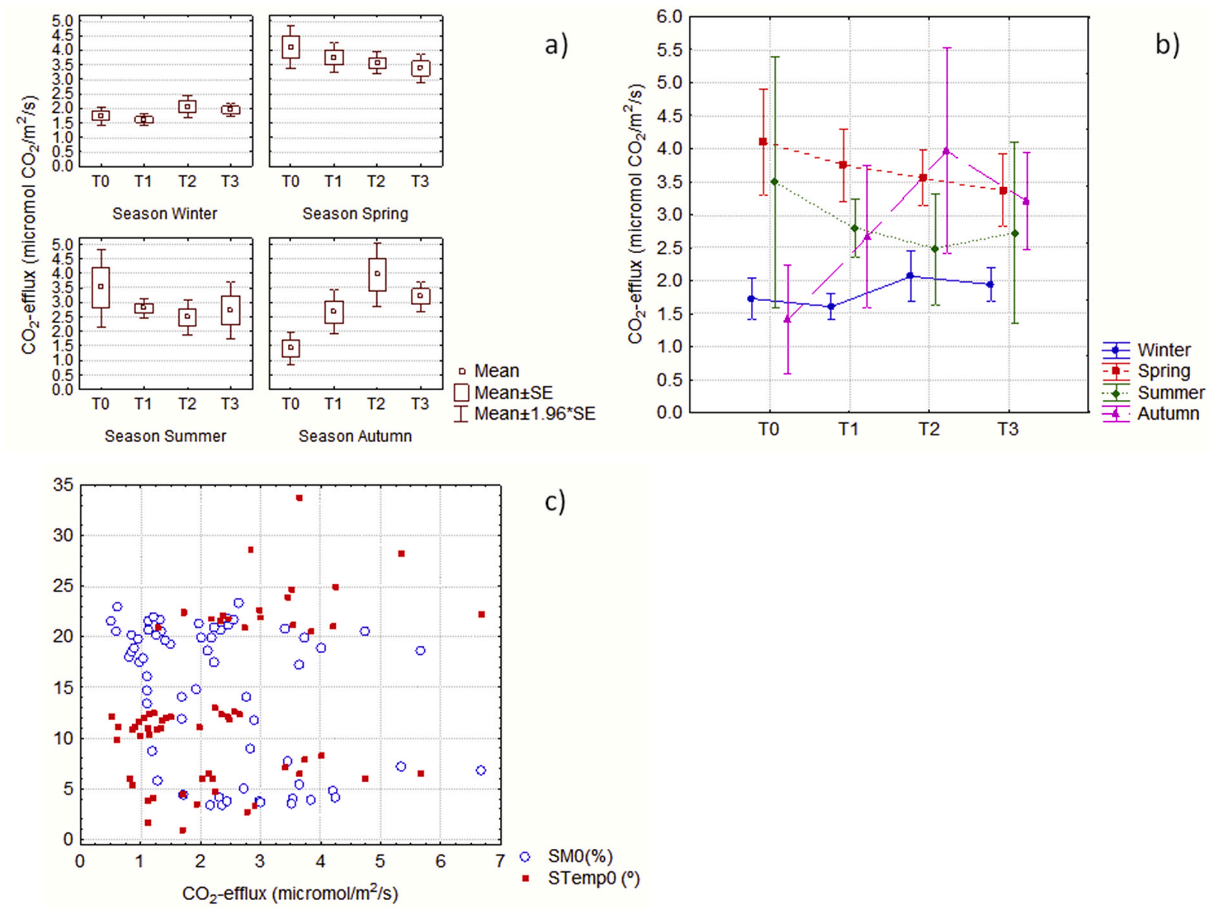

Fig. 7. Features of CO_2 emissions; a) box and whiskers diagrams of seasonal distribution of CO_2 emissions for the different treatments; b) Interactions of treatment and season on CO_2 emissions; c) Scatterplots to show the correlations of CO_2 emissions with soil moisture at a depth of 0 and 10 cm (SM_0) and spatial surface mean temperature ($STemp_0$) for the same (T0 = control, bare soil; T1 = treatment with a residue rate of 7.5 t ha^{-1}; T2 treatment with a residue rate of 15.0 t ha^{-1} and T3 treatment with a residue rate of 30.0 t ha^{-1}; 0 = surface measurement, $STemp_0$; 10 = soil depth at 10 cm, $STemp_{10}$; SE = standard error).

(2016), Fernandez-Romero et al. (2016) and Bound (2018) also highlighted the increase in SOC derived from the addition of olive pruning residues, in other management methods. However, both studies were carried out under very different conditions in terms of the type of experiment and quantity of residues, and cannot therefore be directly compared. Rapullo et al. (2012) quantified a substantial increase in soil organic matter in a 2-year-study where rates of pruning residues over 26.5 t ha^{-1} were applied in an organic olive orchard. From the beginning, an increase in soil organic carbon for depths between 0 and 5 cm was found (between 1.3 and 1.7%). These results agree with the rise in SOC observed in our study for the treatments with 15 t ha^{-1} and 30 t ha^{-1} of approximately 1.7% at a depth of 10 cm. On the other hand, Ordóñez et al. (2007) found no significant effects on SOC associated with the application of pruning residues at rates of between 1.3 and 3 t ha^{-1} (associated with extensive olive groves) for 6 years. Li et al. (2021) suggested an interval of 6 and 8 Mg ha^{-1} as a reference application rate of organic mulches for runoff and erosion control under various environmental conditions whereas Jordán et al. (2010) highlighted that rates > 10 Mg ha^{-1} of straw did not increase soil organic carbon. In our study, the improvement of SOC was only significant for high residue rates >15 t ha^{-1}. In extensive olive groves, where residue rates must be below 3 t ha^{-1} and are usually applied every 2 years, the expected effects on SOC accumulation should not be relevant, in particular if they are uniformly distributed.

- Respiration showed a complex seasonal pattern, where the lowest temperatures of winter and autumn with higher moisture of soil and/or mulch due to the precipitation, led to an increase in CO_2 emissions in the treatments with the highest residue rates (T2 and T3). In contrast, during summer and spring, the bare soil presented the highest respiration values. The loss of water content of the residues, together with the higher increase of soil temperature under the residues for T2 and T3 at the end of spring and summer, could cause worse conditions for the microbiota, which would notably reduce the annual mineralization and enable more organic carbon to be stored (Almagro et al., 2009). Maestre et al. (2013) observed a slightly lower annual range of variation in soil CO_2 efflux (between 0.29 and 2.75 μmol $CO_2.m^2.s^{-1}$) when they evaluated the impact of the increase in temperatures, precipitation and biocrust cover for dryland natural vegetation in gypsum soils. In addition, for their different treatments, they detected that warming tended to either increase, or have no effect on, soil CO_2, which agrees with the correlations presented in Fig. 7c. In contrast, Hou et al. (2016), observed that CO_2 efflux was notably higher in warmed soil as compared with non-warmed soils under the managements of no till and conventional tillage in an agricultural semi-area area in China where wheat and summer maize were cultivated.
- Finally, the orchard studied might be representative of new areas dedicated to super-intensive olive crop in Southern Spain, although the fact that only a clay loam soil was evaluated may be considered a limitation of this study. However, the temporal length of our survey enables us to lay the foundations of new analyses and to provide input data for subsequent modeling of organic carbon under different environments in the short- and medium-term. It is essential to stress

that mulching by using pruning residues is becoming increasingly popular among olive farmers in Southern Spain, due to its cost, which is lower than the use of a cover crop in extensive hillslope olive groves (Calatrava and Franco, 2011). Therefore, the optimization of the use of this mulching technique is in high demand from these farmers and its impact on soil and water management may prove to be of great importance at an economic and environmental level.

5. Conclusions

The benefits of using pruning residue mulch on water conservation in olive groves must be related with rates of fresh pruning residues higher than 7.5 t ha^{-1}, whose high yield can only be associated with super-intensive olive groves, where a high degree of soil cover is also expected. The low impact of the quantity of residues on soil moisture over the year can be explained by the dramatic variations in residue moisture contents due to the typical Mediterranean regime of temperature and water deficit. It seems that only when the residues are still humid during the spring, are they efficient in water conservation. Moreover, there was not a significant correlation between pruning residues rates and soil surface temperatures during the summer compared to bare soil, thus, there is not a serious risk of accidental fire associated to its use.

A threshold of 15 t ha^{-1} of pruning residues resulted in a notable increase in soil organic carbon at depths of 0 and 20 cm. Thus, because mineralization takes place with residue rates of 7.5 t ha^{-1}, the main take-home message of the present study is the suitability of concentrating the pruning residues in only some of the lanes. Consequently, it is difficult to obtain improvements in soil organic carbon derived from pruning residues in extensive olive groves due to the low amount of pruning residue, the uniform spatial distribution and the low periodicity of pruning (2 years). Finally, the worse conditions of higher temperature for the microbiota living below greater residue rates during the warm seasons must reduce annual mineralization, and relatively more soil organic carbon is stored when the pruning residue rates are above 15 t ha^{-1}.

Credit author statements

Encarnación V Taguas: Conceptualization; Investigation, Methodology, Writing; Supervision; **Víctor Marín-Moreno:** Conceptualisation; Investigation; Methodology; **Concepción M Díez:** Conceptualization, Investigation; Resources**;** Writing**; Luciano Mateos:** Conceptualization; Investigation; Resources; **Diego Barranco:** Conceptualization**,** Investigation, Resources. **F Javier Mesas:** Methodology; Investigation; Resources**,** Software**; Rafael Pérez:**Methodology,Resources; **Alfonso García-Ferrer:** Resources**; José L Quero:** Conceptualization; Investigation, Resources, Writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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