Effect of sustainable management of olive tree residues on soil fertility in irrigated and rain-fed olive orchards

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ABSTRACT

Olive trees are a major source of agricultural residues. Strategies based on different management of organic amendments have been reported to increase soil fertility. The effect of sustainable organic matter input practices (application of shredded pruning residue and olive residue compost to soil) on soil properties in irrigated and rain-fed olive groves was investigated. The study took place in 40 olive groves in the region of Peza, island of Crete, Greece during a 5-year period (2012–2017). The results showed that olive trees play an important role in soil nutrient conservation under semi-arid conditions in the Mediterranean basin. The addition of olive tree residues, in combination with conservation tillage practices, improved soil fertility over the experimental period. Most of the soil properties were favored by irrigation. In olive soil parcels receiving organic materials the soil organic matter and the total nitrogen were increased in irrigated fields. The ability of surface soil to sequester carbon and nutrients beneath the tree canopy of olive groves was high. It is recommended that sustainable soil management practices should consider soil fertility variability of olive orchards.

Key words | carbon inputs, chemical properties, irrigation, microbial properties, olive groves, soil

INTRODUCTION

Olive (Olea europaea L.) is a widely cultivated tree crop in the Mediterranean region. About 70% of the olive orchards in the world have traditionally low productivity, mainly due to the lack of appropriate management systems. The new intensively cultivated orchards have suitable productivity but are often associated with adverse environmental impact. Inappropriate cultivation practices (CP) (i.e. excessive tillage, weed control by tillage and chemical treatment, the lack of use of organic amendments, burning of pruning residues in situ), in combination with the Mediterranean climate of Greece, lead to depletion of soil organic matter (SOM), erosion, desertification and degradation of water resources. On the other hand, strategies based on changes in the management of organic amendments have been reported to increase the C stored in soil, to enhance soil structure, increase soil fertility, decrease soil erosion and reduce atmospheric CO₂ (Sánchez-Monedero et al. 2008; Gómez et al. 2009; Russo et al. 2015). In particular, in recent years, the use of cultivation systems that might be able to improve or preserve soil quality, health, and fertility in olive orchards is highly recommended. In most Mediterranean countries, olive trees are a major source of agricultural residues. The cultivation of olive trees produces a large quantity of biomass, such as branches of different thickness and leaves. At the same time high loads of both liquid and solid olive mill wastes are being produced during the olive oil extraction procedures (Calatrava & Franco 2011; Koubouris et al. 2017; Kavvadias et al. 2018). Actually, the sustainable management of olive tree pruning can positively affect soil moisture,
nitrogen and carbon dynamics in soils (Gómez-Muñoz et al. 2016), improving soil fertility. Mulch using plant residues is becoming increasingly popular with farmers, because it reduces both the need for weed control measures (Calatrava & Franco 2011) and soil and nutrient losses (Rodríguez-Lizana et al. 2008). Mulching helps to ensure partial weed control because when the mulch decomposes it forms a physical barrier and produces allelopathic substances (IOOC 2007). Moreover, in recent years mulching has become one of the best options for increasing irrigation efficiency and enhancing the efficient use of rainfall by crops in arid and semi-arid areas (Farzi et al. 2017).

One of the most important factors affecting soil fertility in olive groves is the input of organic matter as compost to soil. Olive tree prunings and leaves after shredding have been used as a bulking agent for composting with other organic residues with encouraging results (Manios 2004). Montanaro et al. (2012) reported that when the long-term application of chipped pruning tree residues is combined with the application of compost in soil in Mediterranean tree crops, then organic matter is substantially increased. Another sustainable management technique is cover crops and green manure which has been shown to improve soil’s physical and chemical fertility, especially in the upper layers (Gómez et al. 2009; Ramos et al. 2010; Goss et al. 2013). Its main benefit is the enhancement of soil nutrients and organic matter, microbial activity and water retention capability. Nieto et al. (2012) reported that the use of cover crops and the elimination of tillage practices significantly improves soil quality in Mediterranean olive groves. Minimum tillage or no tillage, when combined with reduced use of chemical fertilizers or olive residues, caused reduction of soil erosion and improvement of soil quality (Montes-Borrego et al. 2013; Fernández-Romero et al. 2016).

Olive orchards are traditionally managed as rain-fed crops. In recent years water demand for olive orchards has increased in the Mediterranean basin, particularly with reference to the plantations of high-density olive orchards. Nevertheless, although several studies have shown positive effects by increased water supply to olive trees (Gomez-Rico et al. 2007; Gucci et al. 2007), irrigation can often have an adverse effect on the properties of the soil and hence the productivity (Henr & Hogg 2005). The adverse effects result from the water irrigation quality, the application method and soil properties (IOOC 2007). Despite the significance of irrigation there are not many studies on the influence of irrigation on soil organic carbon (SOC) contents and microbial properties while studies that directly compare SOC contents on irrigated and non-irrigated fields are rare, especially those on arid and semi-arid regions (Trost et al. 2014). Although in recent years many authors have shown the beneficial effects of sustainable practices in providing organic amendments on soil properties (Moreno et al. 2009; Montanaro et al. 2012; Koubouris et al. 2017; Kavvadias et al. 2018), their implementation in olive groves under different irrigation regimes and the prevailing Mediterranean conditions have not yet been systematically tested.

On the basis of the foregoing, the success of soil management in maintaining its quality depends on understanding the way that soil responds in agricultural practices (Grebrekidan & Negassa 2006). A LIFE+ project was initiated (oLIVE-CLIMA; LIFE 11/ENV/000942) aiming to trial the introduction of new CP for tree crops, in order to find a cost-effective means of mitigating and adapting to climate changes. The aim of this paper was to analyze the influence of the addition of organic amendments (application of shredded pruning residues, application of compost of olive mill wastes and tree prunings) and irrigation conditions (irrigated and rain-fed olive groves) on the main soil chemical properties (total organic carbon, total nitrogen (TN), inorganic nitrogen, humic and fulvic acids (FA), available P, and exchangeable K and Mg), as well as microbial properties (soil basal microbial respiration and microbial biomass carbon) at two soil depths (0–10 cm and 10–40 cm). Variation of soil properties with increasing distance from the tree trunk was also examined.

**METHODS**

**Study site and soil analysis**

The area of study is located in the island of Crete and in particular in the region of Peza (Prefecture Heraklion). The climate, according to the Köppen–Geiger classification, is characterized as Mediterranean with hot, dry summers
(classified as Csa). Mean maximum monthly temperature is 26 °C (July–August), mean minimum is 12.1 °C (January–February), mean annual is 18.7 °C and mean annual precipitation 460 mm. Olive is a strategic cash crop for Crete because 43% of the agricultural area is cultivated with olive trees which are adaptable to water scarcity, although water availability maximizes yields (Iniesta et al. 2009). The soil moisture regime is xeric and moisture deficit occurs from mid-April to October. The study area consists of various geomorphological elements, and soils are located mostly on alluvial and colluvial materials. Limestone parent material dominates, especially marbles and dolomites. Mineralogical composition of the parent material, topography and degree of slope and exposure, dry climate condition, land use practices and other anthropogenic activities have an important effect on soil formation and have resulted in different soil types also.

Forty olive groves were selected. The size of soil parcels varied between 0.5 and 3 hectares. CP related to organic matter addition (addition of shredded pruning residues on soil, addition of olive residue compost) were applied on half of the irrigated (IR) and rain-fed (RF) soil parcels (treated soil parcels), while the remaining ones (20) were used as control (C) soil parcels and conventional soil management techniques were implemented. However, in many of the control fields reduced tillage and/or no-tillage had been practiced. Therefore combinations of cultivation and irrigation practices (IP) were identified as follows: IR-C = irrigated soil parcels-control; IR-CP = irrigated soil parcels receiving organic amendments; RF-C = rain-fed soil parcels-control; RF-CP = rain-fed soil parcels receiving organic amendments.

With regard to CP, soil was supplemented with chopped pruning residues from the same grove at approximately 6.9 t/ha (fresh weight) each year of the period 2013–2017. Compost was derived from recycling byproducts of a 3-phase olive mill, mixing olive pomace, leaves and chopped pruning residue at a ratio of 1:1:2, where 2 kg CO(NH₂)₉ per m³ of mixture was added. The compost was supplied once every autumn in the years 2013–2017, at a rate of approximately 1.9 t ha⁻¹. The compost dose to be applied depended on the available amount of the materials derived as byproducts from the cultivation of olive groves. In addition, weeds were also maintained and cut before the spring of every year of the period 2013–2017 and were left on the soil. The added dose of cover vegetation was estimated to be approximately 4.7 t/ha/year. Table 1 shows the chemical composition of added materials. Pruning was done each year in December and January and the pruning biomass was chipped and evenly distributed. Soil parcels receiving organic materials were also subjected to conservation tillage practices.

A soil sampling campaign took place during the 5-year (2012–2017) period of study and particularly in December 2012–February 2013 (Year 1), January 2015–February 2015 (Year 3) and December 2016–January 2017 (Year 5). There was no addition of organic materials in the first year of soil sampling (Year 1). In each soil parcel six composite soil samples were taken from 0–10 cm depth, at equal intervals, along a straight line joining the trunk of the tree with the middle of the distance from the nearest tree of the next tree series. The first three samples were under the tree canopy (UTC) and the next three were outside of the tree canopy (OutC). An additional composite sample was taken at a depth of 10–40 cm.

Soil analysis was carried out via standard methodologies (Page et al. 1982). Determination of SOM was based on the spectrometric determination of organic carbon sulfuochromic oxidation (ISO 14235; ISO 1998). A conversion factor of 1.72 was used to convert organic carbon to organic matter. Total N (TN) was determined by the Kjeldahl method (ISO 11261; ISO 1995); available P (Pavail) was determined by sodium hydrogen carbonate extraction (ISO 14263; ISO 1994); exchangeable K (Kexch) and exchangeable Mg (Mgexch) using BaCl₂ extraction (ISO 11260; ISO 1994). Determination of NH₄⁺ and NO₃⁻ was performed in 1:10 water extracts using Dionex-100 Ionic Chromatography (DX 1-05, USA). Humic acids (HA) and FA in soil samples were determined according to Metson et al. (1979). The microbial activity in soil samples was measured by the amount of CO₂ evolved from moist (50–60% of water-holding capacity) soil samples incubated at 22 ± 2 °C, for 24 h. The CO₂ evolved was determined by titrating 10 mL of the NaOH solution with 0.1 N HCl (Ohlinger 1995). The basal respiration (BR) was expressed as mg CO₂-C kg⁻¹ soil h⁻¹ on a soil dry weight basis (105 °C, 24 h). Microbial biomass C (MB-C) was determined by substrate-induced respiration, after the addition of 1% glucose (Anderson & Domsch 1990) and expressed as mg C kg⁻¹ dry soil.
**Statistical analysis**

Data were subjected to analysis of variance (ANOVA) using period of soil sampling (T), IP, cultivation practices-organic matter inputs (CP) and sampling location (SL) as factors. The data were first tested for homogeneity of variance and normality (Shapiro-Wilk’s W test) and then were subjected to a multifactorial analysis of variance followed by Duncan’s multiple range \((a = 0.05)\).

**RESULTS AND DISCUSSION**

**Changes of soil properties with year of soil sampling (T)**

SOM significantly increased according to the year of sampling (Table 2). The increase of SOM is the reflection of the relatively lower microbiological activity and therefore low rate of C mineralization (Dersch & Bohm 2001). In fact, BR was significantly decreased with the period of sampling, probably because decomposition was hindered by low soil moisture conditions. Agricultural systems of semi-arid areas of Crete are typified by low rainfall and high temperature mainly during the summer. On the other hand, MB-C was increased at the third sampling period in relation to the previous sampling periods, suggesting a long-term effect on the microbial community. The build-up of a large and active soil microbial biomass is an important pool of accessible nutrients (Gregorich 1994).

As in the case for SOM, TN was increased over the years, and its content was significantly different at the end of the sampling period (Year 5) compared with the first one. The relatively higher levels of TN are the result of immobilization process due to a high C:N ratio of plant residues. Mean C:N ratio of plant residues was 34 for leaves, 82 for small branches and 174 for thick branches (Table 1). The wider the C:N ratio, the larger the amounts of immobilized N. Chen et al. (2014) concluded that the empirical critical C:N ratio of plant residues which cause the immobilization process should be greater than 44. Nitrogen in plant residues with high C:N ratios (>30) is retained by the microbial biomass during decomposition and is released slowly (Ocio et al. 1991; Bremer & van Kessel 1992).

It is worth noting that conservation tillage practices were applied to the soil parcels. Many workers have reported that these practices increase soil carbon, thus contributing to soil stability and to carbon sequestration (Curtin et al. 2000; Álvaro-Fuentes et al. 2008). The enhancement of SOM is a reflection of the greater accumulation of organic residues at or near the soil surface (Nieto et al. 2015). This management practice improves soil water retention and reduces temperature at the soil surface (Farzi et al. 2017), all of which act to reduce the SOM mineralization rate (Guimarães et al. 2013).

With regard to inorganic N, nitrate concentration was significantly increased in Year 5 compared with Years 1 and 3 while the concentration of NH\(_4\) was decreased in the years that soil was treated with organic materials (Years 3 and 5), compared with the initiation of the soil campaign (Year 1). These results indicate higher nitrification rates with increasing sampling period, as well as lower leaching below the root zone due to organic matter accumulation. This result is important taking into consideration that reduced tillage and organic addition practices can contribute to increased soil fertility. Woody plants rely mainly on nitrate to meet their N demands (Huygens et al. 2016).

### Table 1 | Chemical analysis of organic materials

<table>
<thead>
<tr>
<th></th>
<th>C (%)</th>
<th>N (%)</th>
<th>C:N</th>
<th>P (%)</th>
<th>K (%)</th>
<th>Mg (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean values ± standard deviation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin branches</td>
<td>53.8 ± 0.19</td>
<td>0.72 ± 0.22</td>
<td>82 ± 13</td>
<td>0.08 ± 0.02</td>
<td>0.56 ± 0.09</td>
<td>0.16 ± 0.04</td>
</tr>
<tr>
<td>Leaves</td>
<td>52.28 ± 0.13</td>
<td>1.56 ± 0.30</td>
<td>34 ± 7</td>
<td>0.12 ± 0.01</td>
<td>0.80 ± 0.13</td>
<td>0.24 ± 0.08</td>
</tr>
<tr>
<td>Thick branches</td>
<td>54.87 ± 0.50</td>
<td>0.38 ± 0.18</td>
<td>174 ± 52</td>
<td>0.05 ± 0.01</td>
<td>0.19 ± 0.08</td>
<td>0.04 ± 0.01</td>
</tr>
<tr>
<td>Compost</td>
<td>43.2 ± 8.6</td>
<td>2.3 ± 0.7</td>
<td>18.8 ± 7.7</td>
<td>0.20 ± 0.08</td>
<td>0.93 ± 0.33</td>
<td>0.35 ± 0.10</td>
</tr>
</tbody>
</table>
Table 2 | Main factor effects on soil organic matter (SOM), total nitrogen (TN), inorganic nitrogen (NO$_3^-$ and NH$_4^+$), soil basal microbial respiration (BR), and microbial biomass carbon (MB-C)

<table>
<thead>
<tr>
<th>Source*</th>
<th>DF</th>
<th>SOM$^{b}$</th>
<th>TN$^{b}$</th>
<th>NO$_3^-$</th>
<th>NH$_4^+$</th>
<th>BR$^{b}$</th>
<th>MB-C$^{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of sampling (T)</td>
<td>2</td>
<td>69.01***</td>
<td>6.54**</td>
<td>4.44*</td>
<td>128.81***</td>
<td>40.732***</td>
<td>78.678***</td>
</tr>
<tr>
<td>Irrigation practices (IP)</td>
<td>1</td>
<td>69.13***</td>
<td>59.91***</td>
<td>0.09 NS</td>
<td>3.26 NS</td>
<td>3.972*</td>
<td>18.931***</td>
</tr>
<tr>
<td>Cultivation practices (CP)</td>
<td>1</td>
<td>0.07 NS</td>
<td>0.40 NS</td>
<td>0.32 NS</td>
<td>0.16 NS</td>
<td>0.914 NS</td>
<td>0.142 NS</td>
</tr>
<tr>
<td>Sampling location (SL)</td>
<td>2</td>
<td>12.36***</td>
<td>25.79***</td>
<td>3.82*</td>
<td>1.67 NS</td>
<td>32.471***</td>
<td>57.295***</td>
</tr>
</tbody>
</table>

Main factor. Mean values ± se:

| T | Year 1 | 3.04 ± 0.13c | 1.56 ± 0.05b | 48 ± 23b | 24.6 ± 1.0a | 0.151 ± 0.006a | 1.105 ± 0.019b |
| | Year 3 | 3.89 ± 0.13b | 1.63 ± 0.06b | 72 ± 17b | 5.2 ± 0.8b | 0.129 ± 0.005b | 0.920 ± 0.020c |
| | Year 5 | 5.46 ± 0.14a | 1.86 ± 0.07a | 111 ± 9a | 4.1 ± 0.6b | 0.109 ± 0.005c | 1.252 ± 0.020a |
| IP | Irrigated fields | 4.95 ± 0.12a | 1.96 ± 0.06a | 82 ± 11 | 7.9 ± 0.6 | 0.129 ± 0.004a | 1.165 ± 0.017a |
| | Rain-fed fields | 3.61 ± 0.11b | 1.46 ± 0.05b | 85 ± 14 | 9.4 ± 0.6 | 0.122 ± 0.002b | 1.045 ± 0.015b |
| CP | Control | 4.07 ± 0.10 | 1.70 ± 0.04 | 81 ± 15 | 11.4 ± 0.6 | 0.128 ± 0.002 | 1.089 ± 0.014 |
| | Organic amendments | 4.61 ± 0.14 NS | 1.72 ± 0.06 NS | 87 ± 12 NS | 4.5 ± 0.5 NS | 0.121 ± 0.005 NS | 1.091 ± 0.019 NS |
| SL | UTC$^{d}$ | 4.55 ± 0.11a | 2.05 ± 0.05a | 104 ± 11 ba | 9.4 ± 0.6 | 0.144 ± 0.012a | 1.236 ± 0.015a |
| | OuTC | 3.91 ± 0.11b | 1.71 ± 0.04b | 85 ± 13 ab | 8.5 ± 0.6 | 0.125 ± 0.012b | 1.079 ± 0.014b |
| | 10–40 cm | 3.64 ± 0.14b | 1.38 ± 0.08c | 58 ± 15 | 8.2 ± 0.9 NS | 0.107 ± 0.022c | 0.954 ± 0.021c |

*Glm model: main factors, values of F: *P < 0.05; **P < 0.01; ***P < 0.001; NS: no significant differences.

$^{b}$OM in % TN mg g$^{-1}$ soil, NO$_3^-$ in mg kg$^{-1}$ soil, NH$_4^+$ in mg kg$^{-1}$ soil, BR in CO$_2$ C kg$^{-1}$ soil h$^{-1}$, BM-C in mg C kg$^{-1}$ soil.

$^{c}$Mean values for each measured parameter within factors (T, IP, CP, SL) with the same letter are not significantly different (P < 0.05); se: standard error.

$^{d}$UTC: under tree canopy 0–10 cm, OuTC: outside tree canopy 0–10 cm.

As organic matter was increased with years of experimentation, nutrient availability was reduced. Available P and K$_{exch}$ were significantly reduced in the last two sampling years compared with the first year of soil sampling, while no significant differences were registered for Mg$_{exch}$ (Table 3). The reduced nutrient availability is partly related to a more sustainable fertilization program where alternative cultivation techniques have been applied. In addition, as SOM increases, cation exchange capacity (CEC) is also increased resulting in the increase of fixation capacity of potassium as well as the complexation of magnesium with organic matter (Thompson et al. 1989; Bertol et al. 2005). It is worth mentioning that solubility of P is affected by soil pH. Zhao et al. (2006) and Yu et al. (2013) reported that for soils with a pH > 6.0, the organic matter in the soil increased P-adsorption. In fact mean levels (± standard deviation) of soil pH were 7.24(±0.16), 7.47(±0.18) and 7.62(±0.22) in years 1, 3 and 5, respectively (data not shown). Moreover, the availability of P is impaired in alkaline and calcareous soil due to the high level of calcium phosphates.

With reference to humic substances, the time of soil sampling was significantly and positively related to HA/FA and HA, indicating higher humification rates and resulting in the conclusion that humification depends on SOM contents, as reported by many authors (González et al. 2005). FA were reduced significantly in Year 3 compared with the first year of sampling while differences between Year 1 and 5 were not significant. The degree of humification is an index that can respond appreciably to the addition of organic matter to the soil (Canali et al. 2004). Our results indicate a relatively higher humification process in the last year of the experimental period; relatively more HA than FA indicate the potentially low mobility of carbon accumulated in the soil (Guimarães et al. 2015).

Effect of irrigation practices (IP)

Most of the soil properties were significantly and positively influenced by irrigation compared with rain-fed conditions, except for inorganic nitrogen (Tables 2 and 3). Many works reported that irrigation significantly affected the chemical and microbial properties of soils (Henr & Hogg 2003). Organic matter, TN, BR and microbial biomass C significantly increased with irrigation compared with rain-fed
conditions, therefore promoting soil fertility (Table 2). This is due to increased soil moisture conditions, which enhance vegetation biomass and the development and activity of microorganisms. Actually the mean HA/FA was significantly higher in irrigated soils compared with rain-fed ones (Table 3), indicating a better microbial turnover efficiency in irrigated parcels (Piotrowska et al. 2011). Among the physical factors, soil moisture can affect humification (Bonifácio et al. 2008). In this study, a higher moisture content in irrigated soil parcels compared with rain-fed ones favored microbial activity and the formation of humus (Stevenson 1994). Moreover, the accumulation of plant residues in irrigated soil parcels can outweigh the rain-fed ones. In addition, the lower humification rates of organic matter in rain-fed parcels are the result of the relatively lower content in nutrients (TN, K<sub>exch</sub>, Mg<sub>exch</sub>, P<sub>avail</sub>). The availability of nutrients is favored by soil moisture. Decreased water availability in the soil reduces the nutrient movement by mass flow and diffusion. Of the nutrient supply mechanisms to plant roots, mass flow was the main mechanism for Ca, Mg and N (Oliveira et al. 2010). Soil moisture affects K availability by affecting both K mobility and root growth (Kuchenbuch et al. 1986) and the improved mobility of P was attributed to movement of P in mass flow (Neilsen et al. 1997).

**Effect of organic matter input practices (CP)**

Organic amendments did not have a significant effect on OM, TN, inorganic nitrogen and microbial properties (Table 2). This may be partly attributed to the short duration of demonstration period of organic matter input practices in soil parcels (soil amendment took place twice during the experimental period). Ferrara et al. (2015) and Jokela et al. (2009) registered limited changes in SOM and other chemical parameters after a soil amendment with various organic materials. They concluded that it may take many years before some soil quality indicators fully respond. Actually, the long-term recycling time of plant residues in combination with compost application can substantially increase OM (Montanaro et al. 2012). Moreover, most long-term studies report changes in microbial biomass and respiration with residue inputs under field conditions (Han et al. 2015). In our study organic amendments did not influence soil microbial properties. Rui et al. (2016) noticed that the difficulty in increasing soil C by recent inputs of crop residue

<table>
<thead>
<tr>
<th>Source&lt;sup&gt;a&lt;/sup&gt;</th>
<th>df</th>
<th>HA&lt;sub&gt;a&lt;/sub&gt;</th>
<th>FA&lt;sub&gt;a&lt;/sub&gt;</th>
<th>K&lt;sub&gt;exch&lt;/sub&gt;</th>
<th>Mg&lt;sub&gt;exch&lt;/sub&gt;</th>
<th>P&lt;sub&gt;avail&lt;/sub&gt;</th>
<th>P&lt;sub&gt;avail&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of sampling (T)</td>
<td>2</td>
<td>16.47***</td>
<td>14.40***</td>
<td>5.41**</td>
<td>1.08 NS</td>
<td>13.89***</td>
<td>3.09*</td>
</tr>
<tr>
<td>Irrigation practices (IP)</td>
<td>1</td>
<td>94.09***</td>
<td>101.74***</td>
<td>19.68***</td>
<td>17.58***</td>
<td>6.19*</td>
<td>16.97***</td>
</tr>
<tr>
<td>Cultivation practices (CP)</td>
<td>1</td>
<td>6.04*</td>
<td>0.45 NS</td>
<td>21.13***</td>
<td>16.17***</td>
<td>60.19***</td>
<td>35.89***</td>
</tr>
<tr>
<td>Sampling location (SL)</td>
<td>2</td>
<td>1.87 NS</td>
<td>4.41*</td>
<td>15.19***</td>
<td>46.52***</td>
<td>6.24**</td>
<td>68.97***</td>
</tr>
</tbody>
</table>

*GLM model. Main factors, values of F: *P < 0.05; **P < 0.01; ***P < 0.001; NS: no significant differences.

<sup>a</sup>HA and FA in mg g<sup>-1</sup> soil; K<sub>exch</sub> in cmolc kg<sup>-1</sup> soil, Mg<sub>exch</sub> in cmolc kg<sup>-1</sup> soil; P<sub>avail</sub> in mg kg<sup>-1</sup> soil.

<sup>b</sup>Mean values for each measured parameter within factors (T, IP, CP, SL) with the same letter are not significantly different (P < 0.05); se: standard error.

<sup>c</sup>UTC: under tree canopy 0–10 cm, OuTC: outside tree canopy 0–10 cm.
may be related to the decrease of microbial carbon use efficiency.

Organic matter inputs significantly reduced FA (Table 3) while no significant changes were detected for HA and consequently the HA/FA ratio was significantly increased, indicating that in soil parcels receiving organic materials SOM would deplete at a slower rate and would be maintained for a longer period (Stevenson 1994).

With regard to nutrients, the application of organic material significantly decreased Kexch. This could be explained by a possible increase in CEC which is expected. Organic matter is a contributor to soil CEC (Thompson et al. 1989) therefore increasing the potassium fixation capacity. In contrast, potassium-magnesium antagonism in soils (Jakobsen 2009) seems to be a contributor to the increase of Mgexch after the addition of organic materials. Available P was also significantly and negatively influenced by organic matter input practices. Organic amendments added to soils may also negatively influence P solubility (Iyamuremye & Dick 1996). Beri et al. (1995) reported that the incorporation of crop residues with large C:N and C:P ratios over a long period can decrease the yield of rice and wheat by nitrogen immobilization and P adsorption in soil. Crop residues with higher P content (>0.24%) increased net P mineralization, while crop residues with low P content (<0.07%) resulted in net P immobilization (Nziguheba et al. 1998). In our study the concentration of P in organic materials was lower than the upper limit, indicating low P mineralization.

A significant organic matter input practices (CP) × IP interaction (p < 0.05) for SOM and TN (Figure 1) revealed that the effect of organic matter addition was dependent on irrigation conditions. Alternative CP significantly increased SOM and TN in irrigated fields, while TN was decreased in rain-fed fields and no effect was recorded for SOM. In semi-arid olive ecosystems favorable soil moisture conditions help the accumulation of organic matter and nitrogen. It is generally accepted that irrigation enhances biomass production and the amounts of above ground harvest residues, which results in larger amounts of SOM (Entry et al. 2004).

**Effect of sampling location (SL)**

Soil chemical and microbial properties were significantly higher UTC compared with outside the canopy (OuTC), except for NH₄⁺ and HA/FA (Tables 2 and 3) indicating that olive trees promote soil quality closer to the tree trunk. The primary mechanism, with which soil fertility is improved, explains that the area under the tree is richer in organic residues compared with the area that lies out of the tree canopy (Soria et al. 2005), due to the accumulation of olive litter; it is richer in SOM pools (e.g. microbial biomass, soluble organic C). In addition, nutrients in soils out of the tree canopy are subjected to leaching due to rainfall, while the replenishment of nutrient loss is limited. Soils under tree canopies were found to have significantly higher levels of soil chemical properties than those in open grasslands (Isichei & Muoghalu 1992). Sanchez et al. (1997) noted that the relatively higher N mineralization rates beneath trees would reflect a higher soil biological activity, due to higher SOC and TN, of the soils under the tree canopies than those in grass lands. In addition, olive tree roots release different organic compounds as exudates which in turn increase microbial activity in the rhizosphere (Huang et al. 2014). Major differences in soil management and its impact on soil properties are related to the presence or not of ground cover beyond that provided by the olive tree canopy (Gómez et al. 2008, 2014). Soil management practices should consider soil fertility variability of olive orchards.

Considering the changes of soil properties according to depth, the concentration of most soil parameters declined with depth, particularly close to the trunk. Significant differences between soil depths 0–10 cm, UTC and 10–40 cm were registered for SOM, TN, NO₃⁻, BR, MB-C, FA, HA, Kexch, Mgexch, and Pavail, indicating that the potential of surface soil in olive groves to sequester carbon and nutrients beneath the tree canopy is high. Differences in chemistry were largely driven by greater inputs of organic matter under the trees. Maximum values of organic matter and nitrogen were also reported in surface soil layers (up to 10 cm) of olive groves (Nieto et al. 2011; Marquez-Garcia et al. 2015). The decrease in microbial biomass and activity was possibly due to the reduction of SOM (Govaerts et al. 2007) and of soil oxygen content (Bhattarai et al. 2015). Moreover the reduced microbiological activity affected plant residues decomposition rates (Wendling et al. 2010).

In conclusion, the results of this study showed that under the current experimental conditions, SOM, TN,
nitrates, HA and microbial carbon were increased over the experimental period. In fact, reduced tillage or no tillage practices applied to the soil parcels throughout the field trials promote SOM accumulation and microbial activity. There were no significant changes in SOM, TN, inorganic N and microbial properties after soil amendment with organic materials. Actually it may take many years before some soil quality indicators fully respond. On the other hand, most of the soil properties were significantly and positively influenced by irrigation compared with rain-fed conditions. The effect was more pronounced for SOM and TN in irrigated fields receiving organic materials. Therefore sustainable agricultural intensification that will improve irrigation can increase soil fertility. Major differences in soil properties were recorded in relation to the distance from the tree trunk. The ability of surface soil in olive groves to sequester carbon and nutrients beneath the tree canopy was high. It is advised that the variability in soil fertility in relation to the distance of the olive tree should be taken into account for increasing the efficiency of best soil management practices and irrigation.

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