Climate change mitigation and adaptation in agriculture: the case of the olive
G. Montanaro, V. Nuzzo, C. Xiloyannis and B. Dichio

ABSTRACT
Agriculture might serve as a mitigation solution through carbon (C) sequestration in soil, in tree biomass and reducing greenhouse gas (GHG) emissions. Increased C is beneficial for some soil structures and functions, improving the use of water and in turn the crop adaptation. This study reports on the synergy between mitigation and adaptation in agriculture through the paradigm of the olive (*Olea europaea*). Through data on net ecosystem productivity and soil respiration, the role of olive groves to store C in tree biomass (from 0.36 to 2.78 t CO$_2$ ha$^{-1}$ yr$^{-1}$) and into soil ($\sim$8.5 t CO$_2$ ha$^{-1}$ yr$^{-1}$) is reviewed. The influence of some management practices on that role is also discussed. The overall climatic impact of olive fruit and oil production has been evaluated also considering GHG emissions by field operations (e.g., pruning, mulching of cover crop, fertilization, harvest, etc.) and by the extraction and bottling of oil. Soil C as interface between climate change mitigation and adaptation has been delineated, linking C-induced improvements in soil properties to increased water storage and reduced run-off and erosion. The outcomes may strengthen the environmental role of agriculture and promote synergistic mitigation and adaptation policies assisting in soil and water resources conservation.

Key words | biomass, carbon, erosion, *Olea europaea*, soil respiration, soil water

INTRODUCTION
The olive tree (*Olea europaea* L.) was domesticated more than 3,000 years ago in the Mediterranean area and has represented an integral component (as fruit and oil) of the Mediterranean diet for millennia to the extent that a coevolution between Mediterranean inhabitants and the olive has been proposed (Ortega 2006; Zeng et al. 2015). The specific drought tolerance mechanisms developed by the olive as a Mediterranean native species have greatly contributed to their longstanding success in dry and warm areas (Connor 2005; Dichio et al. 2015). At present, the recognition of olive products as functional food has renewed interest in their consumption (Shahidi & Kiritsakis 2010). However, olive is among the traditional Mediterranean crops which are now suffering from the land abandonment because of environmental and socio-economic constraints (Rodrigo-Comino et al. 2017).

Up to 98% of the global olive growing area (10.2 Mha) is cultivated in the Mediterranean basin (FAOSTAT 2017) under traditional cropping systems (80–100 plants ha$^{-1}$) while a limited fraction (~1%) has recently shifted toward intensive (200–500 plants ha$^{-1}$) or even super-intensive (up to 2,500 plants ha$^{-1}$) cropping systems (Tous et al. 2010). The main reason boosting that change of grove design is the need to increase crop profitability through the reduction of costs per unit yield. However, the potential for change in that crop design is limited because olives are cultivated mainly in marginal hilly areas (Xiloyannis et al. 2008) unsuitable for high density plantations. Hence, identifying alternative
strategies to improve the profitability of olive groves is highly desirable for socio-economic reasons and ecological and landscape conservation.

Nowadays, an integrated view of agriculture combines the provision of food and fiber with additional functions and services to the extent that an ecosystem service approach has been proposed as the future of land evaluation (Dominati et al. 2016). The regulating services relevant to climate change mitigation that agriculture might provide include the overall reduction of emissions of greenhouse gases (GHG). Agriculture uses up to 70% of global fresh water through irrigation. Hence, increasing soil water reservoirs might contribute to reducing the irrigation need and increase productivity in rain-fed areas. The prevailing climate changes will increase the water demand by crops by 40–250% (Savé et al. 2012), contributing to increasing uncertainties for the future availability of fresh water. Hence, increasing soil water holding capacity might represent an adaptation strategy to face future water constraints.

This confirms that great opportunities for synergy between adaptation and mitigation measures exist in agriculture (Smith & Olesen 2010). Mitigation and adaptation are primary instruments to face climate change. However, they are often managed separately because of poor integration of policies at international and national levels (Duguma et al. 2014). Therefore, this study aimed at improving awareness on synergy between mitigation and adaptation in agriculture through the paradigm of the olive.

The reduction of GHG emissions and the sequestration of atmospheric CO2 by means of crop photosynthesis and the increase of soil carbon stock is pivotal to mitigate climate change (Smith et al. 2008). In this regard, the olive industry might contribute via (1) improving the main carbon stock pools (i.e., tree biomass, soil and litter) and (2) reducing GHG emissions during olive cultivation and oil production.

The present study focuses on the impact of olive grove cultivation on carbon stock pools (ecological approach) and the olive oil production chain on GHG emissions (life cycle assessment (LCA) approach). The paper also examines the mitigation and adaptation synergy, discussing the effect of increased soil organic carbon (SOC) on soil water holding capacity and other regulating services (e.g., reduction of erosion risks).

### Atmospheric Carbon Sequestration: Impact of Olive Grove Ecosystems

Monitoring and quantification of carbon (C), water and energy fluxes between cultivated ecosystems and atmosphere creates the basis for better knowledge of key processes related to the climate change and agriculture relationship. According to the view of most ecologists, the imbalance between atmospheric CO2 uptake through photosynthesis and loss by ecosystem respiration (both autotrophic and heterotrophic) is recognized as net ecosystem production (NEP). Hence, NEP is the balance of all CO2 entering and leaving the ecosystem during a time frame (usually 1 year) (Smith et al. 2010). Hence, values of NEP reflect an ecosystem’s metabolism and its interaction with the environment (e.g., weather, soil water availability) (Chapin et al. 2006). There are also non-CO2 exchanges of C (e.g., methane, volatile organic compounds, erosion, leaching of dissolved organic C) usually not included in NEP calculations. In addition, certain losses or gains of C related to anthropogenic activities (e.g., harvest, supply of organic raw material or fertilizers) are also not included in NEP (Chapin et al. 2006).

As plants live, C is gained for new tissue formation (gross primary production, GPP) and lost for living tissue maintenance (including roots) as autotrophic respiration (Ra). Hence, the balance of that gain-loss represents the net gain in C (net primary productivity, NPP) allocated in the plant dry matter, NPP = GPP – Ra. A significant component of the ecosystem-atmosphere CO2 fluxes is the heterotrophic respiration (Rh) of telluric organisms, thus the net C exchange is represented by NEP = NPP – Rh. The ecosystem is the reference for NEP calculations, thus positive values of NEP indicate that the ecosystem is a sink of CO2, while negative ones indicate it as a CO2 source. The net ecosystem exchange (NEE) is determined in micrometeorological-based measurements of C exchange (e.g., eddy-covariance), considering the atmosphere as the reference, it follows that NEP is equivalent to –NEE.

### Soil CO2 Efflux

Soil respiration (Rd) is a relevant component of the terrestrial C cycle, releasing CO2 each year about 10 times that
released from global fossil fuel combustion (Raich & Tufekcioglu 2000). This supports the idea that a reduction of $R_S$ through the stabilization of humic molecules might help to mitigate GHG emissions from soil (Piccolo et al. 2011). Emissions of CO$_2$ from soil depend on several factors including soil moisture, temperature, root density, abundance of C substrates and soil organism populations (Raich & Tufekcioglu 2000). Some of these factors are involved in the spatial variability of soil respiration existing at a field scale. For example, in tree crops under localized irrigation, there is no soil moisture gradient between row (irrigated) and the inter-row (rain-fed) that generates a gradient in CO$_2$ soil emission (Montanaro et al. 2012).

Figure 1 reports the seasonal changes in $R_S$ recorded at a traditional olive grove (156 plants ha$^{-1}$) located in southern Italy (40°29′N, 16°28′E) using portable gas analyser equipment according to the methodology reported in Montanaro et al. (2012). Measurements show that the increase of $R_S$ detected early in the growing season is consistent with the increase in soil temperature. Thereafter, during the summer $R_S$ conceivably declines because of the soil moisture reduction and the slowdown in root growth (Figure 1). However, eventual precipitation after the summer might promote a regrowth of roots and then an increase in $R_S$ (Montanaro et al. 2012).

Despite the prominence of $R_S$ for the determination of the ecological impact of olive groves (e.g., determination of net ecosystem productivity), information on annual soil CO$_2$ efflux is still limited. Almagro et al. (2009) measured the $R_S$ under the canopy and at inter-canopy positions in an olive grove (10 × 10 m planting density) reporting soil emissions of approximately 30 and 12 t CO$_2$ ha$^{-1}$ yr$^{-1}$, respectively. The soil CO$_2$ efflux reported in this study (Figure 1) generates an annual emission close to 25 t CO$_2$ ha$^{-1}$ yr$^{-1}$ according to the integration curve procedure reported in Montanaro et al. (2017a). Soil emissions in olive groves might even be as high as 43.2 t CO$_2$ ha$^{-1}$ yr$^{-1}$ under a higher plantation density (512 plants ha$^{-1}$) likely because of a putatively higher root density (Bertolla et al. 2014). Soil management strategy (e.g., cover crops, tillage) might be influential on $R_S$ in olive groves, showing higher CO$_2$ effluxes from soil under cover crops (Chamizo et al. 2017; Turrini et al. 2017). Similarly, Saadi et al. (2007) measured the increased CO$_2$ emissions from soil supplemented with olive mill wastewater in the laboratory. This might be due to higher C substances available for microorganisms after cover crop mulching and mill wastewater supply (Raich & Tufekcioglu 2000). Hence, increased $R_S$ could possibly be interpreted as an acceptable environmental cost compensated by other positive benefits derived from increased C supply (see below).

**Net ecosystem productivity**

The carbon sequestration role of tree crops is recognized to the extent that they have been listed among the natural climate solutions able to potentially mitigate climate change (Zomer et al. 2016; Griscom et al. 2017).

Table 1 reports some available information on NEP in various tree crops, showing that olive groves have a fairly high ability to remove C from the atmosphere. This ability seems to decline with tree age likely due to the limited growth of old trees (see last entry in Table 1) (Chamizo et al. 2017). Several natural, climatic (e.g., variations in growing-season length or cloudiness, precipitation) and anthropogenic factors (e.g., cover crops, management of pruning residuals, tillage) might influence C uptake and respiration and in turn generate seasonal and inter-annual variabilities in NEP (Barford et al. 2001; Allard et al. 2008), making comparisons among sites and species difficult to assess. However, olive and citrus trees are
evergreen crops which might differ in terms of leaf C economy compared with deciduous ones (Reich et al. 1995). In addition, considering that the longevity of leaf has been explained in terms of improved C balance and adaptation to environmental stresses (Chabot & Hicks 1982), olive groves might be a suitable natural climate solution sensu Griscom et al. (2017).

**Biomass carbon stock**

Apart from annual newly formed biomass (i.e., fruit, leaves, new shoots and roots) which is the basis for NEP determination, perennial woody crops have a significant potential in terms of climate change mitigation mainly because of the C permanently stored in above- and belowground structures. However, tree crops are not yet considered key contributors to global and national C budgets to the extent that they are ‘historically, generally missing’ from GHG inventory reports (Blujdea et al. 2015; Zomer et al. 2016).

Quantification of the biomass of pruning residuals and permanent structures removed at the end-of-life of the orchard in perennial crops including olive has been the core of several energy use studies (e.g., Velázquez-Martí et al. 2014; Ruíz et al. 2017).

Pruning residues in olive groves might reach 2.4 t ha$^{-1}$ dry matter (annual pruning) or even 4.6 t ha$^{-1}$ (biannual pruning) (Velázquez-Martí et al. 2011; Palese et al. 2013) equal to approximately 0.7 and 1.4 t CO$_2$ ha$^{-1}$ yr$^{-1}$. However, pruning residues are considered unstable sequestration of CO$_2$ because of their relatively fast turnover; thus they are not listed in climate change mitigation procedures (IPCC 2006).

In contrast, the C content in permanent structures (e.g., trunk, branches and coarse roots) available at the end of the life cycle of perennial tree crops represents a C pool that can be reported within the Kyoto Protocol commitments (IPCC 2006). However, the fate of that biomass might be relevant for a CO$_2$ flux to the atmosphere. That is, the renewable biomass resource could be mulched and deposited on the orchard floor, or taken to a biomass power plant, or it could be used in the production of furniture, etc., creating uncertainty for the global warming potential (GWP) determinations within LCA (Fiore et al. 2018 and reference therein).

Table 2 reports the data on C stored in permanent biomass of various olive groves as compared with default IPCC values for dry regions (400–800 mm yr$^{-1}$ precipitation) (IPCC 2006). Considering that a refinement of the IPCC guidelines with updated default values is expected to be issued by 2019 (G. Montanaro, pers. com.), increasing data availability would be in favor of a more accurate future GHG report for perennial crops. In addition, taking into account the longevity of olive groves (>80–100 years) compared with other tree crop orchards (15–20 years), specific information on the olive would be highly valued.

### Table 1 | Annual net ecosystem productivity (NEP) in various tree crops, olive and vineyard

<table>
<thead>
<tr>
<th>Tree crop</th>
<th>NEP (t CO$_2$ ha$^{-1}$ yr$^{-1}$)</th>
<th>Density (plants ha$^{-1}$)</th>
<th>Age (years)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olive</td>
<td>45.9</td>
<td>227</td>
<td>12–16</td>
<td>Nardino et al. (2015)</td>
</tr>
<tr>
<td>Vineyard</td>
<td>29.9</td>
<td>3,077</td>
<td>17</td>
<td>Meggio &amp; Pitacco (2016)</td>
</tr>
<tr>
<td>Olive</td>
<td>28.0</td>
<td>408</td>
<td>4</td>
<td>Testi et al. (2008)</td>
</tr>
<tr>
<td>Apple</td>
<td>15.2</td>
<td>3,333</td>
<td>9</td>
<td>Zanotelli et al. (2015)</td>
</tr>
<tr>
<td>Peach</td>
<td>11.7–17.4</td>
<td>500</td>
<td>14</td>
<td>Montanaro et al. (2017a)</td>
</tr>
<tr>
<td>Apple</td>
<td>13.9</td>
<td>2,632</td>
<td>10</td>
<td>Panzacchi et al. (2012)</td>
</tr>
<tr>
<td>Olive</td>
<td>13.4</td>
<td>285</td>
<td>20</td>
<td>Brilli et al. (2016)</td>
</tr>
<tr>
<td>Orange</td>
<td>4.0$^a$</td>
<td>494</td>
<td>14</td>
<td>Liguori et al. (2009)</td>
</tr>
<tr>
<td>Orange</td>
<td>7.9$^a$</td>
<td>1,000</td>
<td>12</td>
<td>Liguori et al. (2009)</td>
</tr>
<tr>
<td>Olive</td>
<td>2.5–5.1</td>
<td>204</td>
<td>80</td>
<td>Chamizo et al. (2017)</td>
</tr>
</tbody>
</table>

Note that values might have been converted from NEE to NEP based on the relation NEP = NEE – NEE.

$^a$Assuming 0.75 heterotrophic/total soil respiration ratio (Montanaro et al. 2017a).
Soil carbon stock

Recent estimates have quantified the global SOC stock (1 m depth) at approximately 1,500 Pg C representing the largest terrestrial C pool (Scharlemann et al. 2014). Soil has a potential to further store C through appropriate management practices, trapping atmospheric CO2 in soil (Lal 2016). This provided the basis for the ‘4 per mille’ initiative launched at the 21st Conference of the Parties to the United Nations (UN) Framework Convention on Climate Change in Paris (December 2015). The proposal would boost the adoption of strategies to enhance global SOC stock (0.4 m depth) at the rate of 0.4% per year to offset the current annual increase of atmospheric CO2 (Lal 2016). The evaluation of the factual achievement of the ‘4 per mille’ initiative is under debate (Minasny et al. 2017; de Vries 2018). However, increasing C content is affordable through the adoption of best management practices aimed at increasing C input (e.g., recycling of pruning residuals, supply of compost or manure, adoption of cover crops) and reducing soil disturbance (e.g., no or minimum tillage) (Lal 2015). Generally, in woody species, SOC accumulation rates in the top 10 cm soil layer is 50% greater than that under herbaceous species presumably due to a higher C input from leaf litter (Chimento et al. 2016).

Certain agricultural practices (e.g., no tillage, cover crops, supply of organic raw material, recycling of pruning residuals) might increase soil carbon stock and in turn enhance the climate change mitigation potential of agricultural soils (Lal 2015). Aguilera et al. (2015) published a meta-analysis on soil carbon sequestration at various Mediterranean cropping systems as influenced by the typology of practices adopted. The highest mean carbon sequestration rate (~5 t C ha\(^{-1}\) yr\(^{-1}\), 27 cm depth) was achieved by those practices applying the largest amounts of carbon input (exceeding 10 t C ha\(^{-1}\) yr\(^{-1}\)). At a traditional olive grove in southern Italy, the change of management practices from tillage and burning of pruning residues to no-tillage, the adoption of spontaneous cover crops and the mulching of pruning residues had a beneficial effect on soil carbon concentration (from 1.1 up to 1.4%) and in turn on the stock of carbon (0–30 cm depth) at a mean rate of 2.4 t C ha\(^{-1}\) yr\(^{-1}\) (equal to 8.8 t CO2 ha\(^{-1}\) yr\(^{-1}\)) (Figure 2). The beneficial increase of SOC due to certain soil management practices strengthens the relevance of groves as managed ecosystems for climate change mitigation.

Table 2 | Amount of CO2 stored in above and belowground biomass in olive trees (various references) and default IPCC value for that biomass in dry areas (see Table 5.1, Chapter 5, Vol. 4 of IPCC 2006)

<table>
<thead>
<tr>
<th>Description</th>
<th>t CO(_2) ha(^{-1})</th>
<th>t CO(_2) ha(^{-1}) yr(^{-1})</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>60-year old, 100 plants ha(^{-1})</td>
<td>91.4</td>
<td>1.52</td>
<td>Nuzzo, in preparation</td>
</tr>
<tr>
<td>5-year old, n.a.</td>
<td>66.1</td>
<td>13.2</td>
<td>IPCC (2006)</td>
</tr>
<tr>
<td>100-year old, 107 plants ha(^{-1})</td>
<td>36.4</td>
<td>0.36</td>
<td>Almagro et al. (2010)</td>
</tr>
<tr>
<td>11-year old, 330 plants ha(^{-1})</td>
<td>30.6</td>
<td>2.78</td>
<td>Proietti et al. (2014)</td>
</tr>
<tr>
<td>11-year old, 330 plants ha(^{-1})</td>
<td>20.5</td>
<td>1.86</td>
<td>Ilarioni et al. (2015)</td>
</tr>
</tbody>
</table>

Note: for the IPCC value a standard 1:1 ratio between above- and belowground biomass has been considered.

Figure 2 | Variation of the soil carbon stock (0–30 cm depth) recorded at an olive grove after the shift from conventional tillage, burning of pruning residues to sustainable practices (in situ mulching of pruning residues, cover crops).
GHG EMISSIONS DURING UPSTREAM AND CORE PROCESSES OF OLIVE OIL PRODUCTION

LCA is broadly adopted to assess the impact of agricultural food production and processing on GWP, supporting the identification of alternatives to reduce that impact in both annual and perennial crops (e.g., Cerutti et al. 2014; Goglio et al. 2017; Fiore et al. 2018).

However, LCA methodology needs further improvement for standardization of methods (Cerutti et al. 2014; Notarnicola et al. 2017). LCA studies in the olive production chain might differ in terms of boundary layer, functional unit, scenario considered and the focus production process (e.g., field, oil extraction and bottling, recycling of waste material, etc.) (Rinaldi et al. 2014; Tsarouhas et al. 2015; Christoforou & Fokaides 2016; Romero-Gámez et al. 2017; Proietti et al. 2017). The life cycle inventory might also represent a source of variability because it is influenced by the type of management adopted (e.g., irrigation, rain-fed, tillage, cover crops, density plantation) (Russo et al. 2015).

The comparison of various LCA studies was not the purpose of the present paper. In this study, the impact on GWP of olive cultivation, oil extraction and bottling has been inferred from similar LCA studies (Rinaldi et al. 2014; Tsarouhas et al. 2015; Proietti et al. 2017). In these studies, orchards were rain-fed and planted traditionally (average 260 plants ha\(^{-1}\) plantation density). The upstream operations identified were pruning, mulching of pruning residuals and cover crops, fertilization, pesticide applications, harvest and transportation of olive fruit to the mill. The downstream processes were the extraction and bottling of oil (Table 3). Considering these olive ecosystems, the mean annual values of upstream emissions represented approximately 55% of the total CO\(_2\)eq emitted from cultivation to bottling. Interestingly, the amount of C sequestered in permanent structures and soil overcome emissions due to downstream operations (Table 3). This supports the idea that biogenic and soil carbon changes might be included in agricultural LCA (Goglio et al. 2015; Fiore et al. 2018) for a more accurate environmental impact assessment of olive fruit and oil production.

![Table 3](http://iwaponline.com/jwcc/article-pdf/9/4/633/510196/jwc0090633.pdf)

<table>
<thead>
<tr>
<th>Description</th>
<th>CO(_2)eq ha(^{-1}) yr(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions</td>
<td></td>
</tr>
<tr>
<td>Upstream field operations(^a)</td>
<td>+0.66</td>
</tr>
<tr>
<td>Extraction, bottling (1 L) of oil(^b)</td>
<td>+0.53</td>
</tr>
<tr>
<td>Sequestrations</td>
<td></td>
</tr>
<tr>
<td>Permanent structures(^b)</td>
<td>-1.60</td>
</tr>
<tr>
<td>Soil(^f)</td>
<td>-8.81</td>
</tr>
</tbody>
</table>
| Note: The atmosphere has been considered the reference, thus + and – signs indicate net emissions to and removals from the atmosphere, respectively.  
\(^a\) Averaged from Rinaldi et al. (2014), Tsarouhas et al. (2015) and Proietti et al. (2017).  
\(^b\) See Table 2 for references.  
\(^f\) Own data redrawn from Figure 2. |

OLIVE GROVE AND SOIL WATER RESOURCE

Olives are mainly cultivated in a low-rainfall environment and their survival depend on tree physiological characteristics and some grove management practices. For example, canopy management under water scarcity has been modeled to maximize grove productivity through the regulation of the canopy cover which is relevant for water evaporation from soil and in turn for tree water availability (Connor 2005). However, improving collection and storage of rainwater in soil is pivotal to maintaining the moisture (and yield) as optimally as possible and to minimize some environmental impacts (e.g., soil erosion, run-off).

Soil management is influential on various soil properties (e.g., porosity, bulk density) and processes (e.g., CO\(_2\) emissions) which are related to climate change issues (Montanaro et al. 2012; Mangalassery et al. 2015). Conserved agricultural practices (including reduced tillage, no-till, permanent organic soil cover by retaining crop residues, cover crops) have been developed as both mitigation (reduction of GHG emissions) and adaptation tools (reduction of run-off, enhancement of water retention preventing soil erosion) (Mangalassery et al. 2015).

The relationship between soil management and the ability of soil to deliver a set of ecosystem services (including water supply to crop) is mediated by its carbon content, consequently under low SOC concentration some soil structure...
and functions are impaired (Palm et al. 2014; Demestihas et al. 2017; Montanaro et al. 2017b). Hence, increasing SOC would be beneficial for soil water storage and in turn for crops.

For example, at a Mediterranean rain-fed olive grove under soil tillage, SOC values were approximately 40% lower than that at a sustainable one (no tillage, cover crops and recycling of pruning residuals), affecting soil macroporosity and in turn soil saturated hydraulic conductivity (Figure 3). As a consequence of the lower infiltration rate, the amount of water stored in the soil (2 m depth) was ~25% reduced in tilled plots compared with sustainable ones (Figure 3). Soil management (e.g., tillage vs. cover crops) has an impact on run-off and in turn on soil erosion, which is reasonably low in undisturbed soils where SOC tends to be high (Figure 3).

**CONCLUSIONS**

This study provides a view on effective synergy between mitigation and adaptation to climate change in the olive. Olive ecosystems might contribute to mitigate climate change through sequestration of atmospheric CO₂ in tree biomass and soil serving as a natural climate solution. This in turn provides an adaptation benefit due to the enhanced soil functions relevant for storage of rainwater.

The results also emphasize the opportunity to combine information on biome (field stage) and anthropogenic (field and mill stage) GHG emissions/removals if a more detailed environmental impact of olive fruit and oil production is to be determined. This study demonstrated the benefits of a synergistic approach to mitigation and adaptation in olive groves which might increase their resilience and support the implementation of environmentally friendly policies to face climate change and preserve soil and water.

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