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Assessment of carbon sequestration and the carbon footprint in olive groves in Southern Spain

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ABSTRACT

Tree plantations are characterized by their ability to remove CO_2 from the atmosphere and store it in a stable manner in tree structures (trunks, roots and branches) as well as in the soil. The study was conducted in Southern Spain in olive groves and covering an area of 1121 ha, where 22 homogenous plantation units were selected. The Picual and Arbequina varieties were assessed in intensive, super-intensive and conventional plantations as well as in rainfed and irrigated plantations. The net carbon (C) balance in the olive tree plantations was clearly positive, especially in intensive and super-intensive plantations (2.05 and 4.10 Mg C ha^{-1} yr^{-1} on average for all plantations studied). These results are significant for life-cycle evaluations of olive oil and for obtaining the C footprint of olive oil as a final product. Improved practices for soil management, such as the use of conservation tillage and cover crops and reincorporating pruning residues into the soil, can notably increase the net C balance in tree plantations and may even double it in amount. Thus, including the C sequestration rate of olive tree plantations can increase the accuracy of C footprint estimations for olive oil and represents a key factor in marketing the final product according to its environmental benefits.

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Olea europaea; carbon sequester rate; greenhouse gas emissions; soil organic carbon; biomass carbon

Introduction

Compared with the conventional industrial and transportation sectors, when the agricultural sector is properly managed, it can balance CO_2 emissions to the atmosphere and store it as carbon (C) in plant biomass and in the soil. C sequestration occurs when a combination of farming practices increases the C stored in soils [1,2]. The effect of practices such as tillage system, crop rotation, tree plantation and fertilization management differs depending on the soil type, farming system, residue management and climate [3–7].

Tree plantations are characterized by their ability to remove CO_2 from the atmosphere and store it temporarily within the tree parts (trunks, roots, branches, leaves and fruits) and soil over long time periods. Therefore, tree plantations are known to have a higher potential for C sequestration than annual crops have. The C stored in trunks, branches and roots is quite stable. However, previous research must be applied to determine the CO_2 removal capacity by a tree system and C sequestration in the soil. A number of studies have assessed the production and net C budget in forest ecosystems, although few studies have focused on crops, which is partly because of the difficulties and uncertainties related to estimating the amount of C in farmlands [8–12].

The term “carbon footprint” is relatively new, although the methods supporting it are well established because they were previously developed for a wide variety of environmental issues. There is no widely accepted or concrete definition for C footprint in use, although there is a general notion of its meaning and status. An inclusive definition that attempts to incorporate all possible applications has been proposed by Peters [13]: “the C footprint of a functional unit is the climatic impact expressed as a specific measurement when all relevant emission sources, sinks and storage within a system limited spatially and temporarily are considered” (p. 245).

The C footprint is one of the most widely used indicators for identifying, synthesizing and communicating the potential environmental impacts caused by a process or activity. Therefore, a product’s C footprint is intended to quantify the greenhouse gases (GHG) emitted to the atmosphere during the manufacture and sale of a product, from the raw material acquisition to residue management, allowing consumers to decide which food to buy based on the emissions produced. The concept of a C footprint is important for companies, consumers and politicians. Investors analyze the C footprint as an indicator of investment risks, purchasing managers are interested in the C footprint associated with supply chains and consumers are

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increasingly interested in products with labels showing the C footprint [13,14].

The C footprint is related to climate change and represents a key component of the corporate social responsibility of companies. Numerous countries, including France, the USA, Canada, the United Kingdom, Switzerland, Japan, Australia and Germany, have passed laws and implemented rules regarding the C footprint of products and services. In addition, an increasing number of food companies are disclosing information on the C footprint of their products. According to a recent survey, 72% of Europeans are in favor of requiring companies to show the C footprint of their products.

The agriculture and forestry sectors are the only sectors that can remove CO_2 from the atmosphere; thus, the term "C balance" may be more appropriate than "C footprint" with regards to agriculture because many crops can produce a positive balance by acting as net CO_2 sinks (depending on production technique). Thus, Clay et al. [15] have used the term "partial C footprint" and even "negative C footprint."

A number of methods [14] have been standardized internationally for the calculation of C footprints, and they are applied to products as well as services and only consider GHG emissions associated with processes. When these methods are applied to the agri-food industry, the C footprint is obtained by considering the GHG emissions associated with the raw materials (wheat, olives, oranges, etc.) as well as those produced during the manufacturing process (bread, baked goods, oil, juice, etc.). The amount of potentially sequestered C generated when producing raw materials is omitted. Thus, the standardized methodologies for obtaining the C footprint have not been developed specifically for agriculture or the agri-food industry.

Previous studies of olive tree plantations have provided information on the net C sequestration [7,16], C exchange and water use efficiency in irrigated olive groves [17], and models have been developed to determine the growth potential of an olive tree's aboveground structures as a tool to estimate C sequestration [18]. In Southern Italy, Sofo et al. [16] obtained the average values for the amount of CO_2 captured as a function of age, olive tree density, and aboveground and belowground structure differences, and mean values of 2.74 and 9.54 Mg ha^{-1} yr^{-1} have been observed in young and mature plantations, respectively. Testi et al. [17] used eddy covariance to measure the CO_2 flux in an irrigated olive grove in Córdoba during different leaf area index (LAI) periods. The results of the study suggest that olive groves watered by drip irrigation must be investigated regarding their C exchange and appropriate calculations, and such results cannot be easily applied to other biomes. Finally, Villalobos et al. [18] have calibrated and validated a simple model based on radiation-use efficiency (RUE) to study the growth and yield of different olive tree varieties in Southern Spain, and they estimated the C sequestration potential in an intensive olive tree plantation under irrigation at 7 Mg CO_2 ha^{-1} yr^{-1}. However, there are no studies on the sequestering and footprint of C that integrate different plots located in a large area of cultivation with different soil types, cultivars, planting densities and irrigation systems.

The objective of this study was to assess C sequestration and determine the C footprint for a set of olive tree plantations in Southern Spain with different plantation densities and cultivation systems for Picual and Arbequina varieties. The aim was to develop a predictive model capable of estimating the amount of C stored in the biomass of olive tree plantations.

Materials and methods

Study sites

The study was conducted over an area of 1121 ha located in the provinces of Seville, Cordoba, Cadiz and Jaen (Southern Spain) (Figure 1) and investigated 22 homogeneous unit olive groves (HUOGs), each owned by the same farmer. Each HUOG presents similar characteristics, including soil, variety, age, plantation density, cultivation system (rainfed or irrigated) and farming practice (Table 1). Tillage operations differ according to homogeneous units although minimum tillage (roller, disk harrowing and weeding machine) with the use of cover crops predominated in most cases (Table 1). The Picual and Arbequina varieties are cultivated in the studied HUOGs, which include intensive, super-intensive and traditional plantations, and rainfed and irrigated cultivation (Table 1).

The broad differences between the studied HUOGs in terms of location (weather), variety, age and plantation density are essential for obtaining a wide range of data, and have been useful for confirming variability in the values of C sequestration and balances in olive tree plantations.

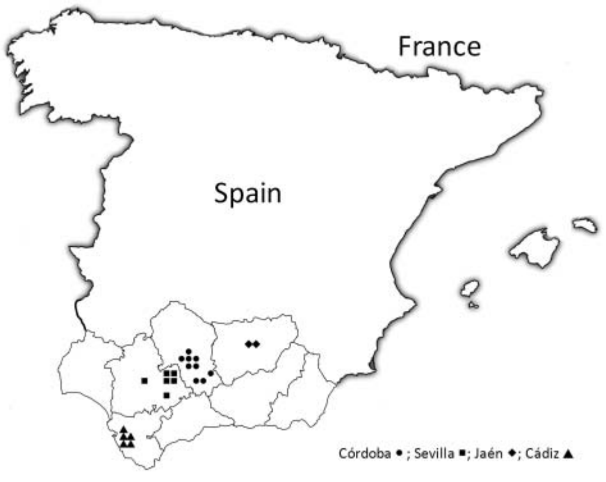

Figure 1. **Map with the study areas, indicating the homogeneous unit olive groves.**

The olive tree plantation units were grouped by plantation density (number of trees ha^{-1}) as follows: conventional, including traditional mature plantations that are no longer developed, with 80 to 100 trees ha^{-1}; intensive, with densities between 200 and 300 trees ha^{-1} and different plantation frames; and super-intensive or hedgerow, with densities ranging from 500 to 2000 trees ha^{-1}. The different plantation frames, density of trees per hectare and soil characteristics are shown in Table 1.

Field study

Olive tree uprooting

Previously, a control test was performed with three specimens each of the Picual and Arbequina varieties from 15-year-old intensive plantations. These specimens were uprooted, and their biomass volume was obtained by dasometric analysis before uprooting and compared with the real weight and volume measured directly from the uprooted olive trees to confirm the reliability of the dendrometric method. After uprooting the selected trees, the individual aboveground components (trunk, branches, twigs) were weighed in the field and samples of all parts were put in a oven at 105 °C until they reached a constant weight [19]. The dry weight of the tree was calculated by multiplying the percentage of dry weight of each individual component by their fresh weight. Multiplying the average amount of measured trees' dry weight by the number of trees per hectare, the dry weight per hectare was obtained.

The tree uprooting was performed with a New Holland telehandler on a sandy loam soil in wet conditions. Subsequently, an excavation was made recovering the roots remaining in the soil. These were generally of less than 0.5 cm in diameter, representing around 20% of the total weight of the roots of each tree. The roots were separated from the trunk and weighed. For the aboveground portions of the trees, trunks and branches of different sizes up to 2 cm in diameter were weighed, and their volume was measured separately. The shoot/root ratio was obtained. A Pressler borer [20] was used to collect samples from the roots and branches to determine the wood density of each part. Different portions of vegetable matter were dried in an oven at 70 °C to obtain the amount of dry matter. Finally, the material was shredded separately to analyze the C content.

Biomass volume measurements in olive tree plantations

Three representative trees were selected in each HUOG, and the height and the largest and smallest diameter of the trunk and main and secondary

Table 1. **General and soil characteristics of homogeneous unit olive groves (HUOGs).**

HUOGs	Location	Area (ha)	Variety	Plantation age	Plantation frames (m^2)	Number of olive trees ha^{-1}	Cultivation system	Cover crops	Pruning residue incorporation	Texture	pH	Organic matter (%)	Carbonates (%)
1	Aguilar de la Frontera (Co)	35	Picual	1994	7 × 7	204	Irrigated	Native	Yes	Loam	8.51	1.63	66.1
2	Luque (Co)	45	Picual	1970	11 × 11	83	Rainfall	Native	Yes	Loam	8.51	1.04	66.1
3	Arahal (Se)	54	Arbequina	2009	5 × 1.5	1333	Irrigated	No	No	Sandy-clay-loam	8.33	2.66	5.4
4	Carmona (Se)	46	Arbequina	2007	3.75 × 1.35	1975	Irrigated	Native	No	Sandy-clay-loam	8.33	1.53	5.4
5	Écija (Se)	14	Arbequina	2007	3.75 × 1.35	1975	Irrigated	No	No	Sandy-clay-loam	8.12	0.58	7.7
6	Écija (Se)	60	Arbequina	2007	3.75 × 1.35	1975	Irrigated	No	No	Sandy-clay-loam	8.12	1.58	7.7
7	Écija (Se)	17	Arbequina	2005	7 × 5	286	Irrigated	No	No	Sandy-clay-loam	8.12	0.83	7.7
8	Santaella (Co)	245	Picual	2007	8 × 6	208	Rainfall	Native	No	Sandy-clay-loam	8.33	2.01	5.4
9	Santaella (Co)	154	Arbequina	2007	7 × 5	286	Rainfall	Native	No	Sandy-clay-loam	8.08	1.93	21.2
10	La Rambla (Co)	22	Arbequina	2006	4 × 1.35	1852	Irrigated	Native	No	Sandy-clay-loam	8.33	1.53	5.4
11	La Rambla (Co)	45	Picual	2006	8 × 6	208	Irrigated	Native	No	Sandy-clay-loam	8.33	1.71	5.4
12	La Rambla (Co)	7	Picual	2006	7 × 7.5	190	Irrigated	Native	No	Sandy-clay-loam	8.33	1.10	5.4
13	La Carlota (Co)	51	Picual	1995	9 × 4.5	247	Irrigated	No	No	Sandy-clay-loam	8.33	0.70	5.4
14	Écija (Se)	25	Picual	1995	8 × 6	208	Irrigated	No	No	Sandy-clay-loam	8.33	1.60	5.4
15	La Carlota (Co)	53	Picual	1994	8 × 6	208	Irrigated	No	No	Sandy-clay-loam	8.33	1.12	5.4
16	Baeza (J)	25	Arbequina	2001	8 × 2.5	500	Irrigated	Native	Yes	Sandy-clay-loam	7.77	1.02	40.0
17	Baeza (J)	99	Picual	1955	10 × 10	100	Irrigated	Native	Yes	Sandy-clay-loam	7.77	0.28	40.0
18	Jerez de la Frontera (Ca)	23	Arbequina	2005	7 × 6	238	Rainfall	Native	No	Silty-clay	8.3	1.89	27.9
19	Jerez de la Frontera (Ca)	21	Arbequina	2007	7 × 6	238	Irrigated	Native	No	Silty-clay	8.3	1.91	27.9
20	Jerez de la Frontera (Ca)	17	Arbequina	2009	7 × 6	238	Rainfall	Native	No	Clay	8.25	2.22	37.2
21	Jerez de la Frontera (Ca)	35	Picual	1995	8 × 7	179	Rainfall	Native	No	Clay	8.25	2.44	37.2
22	Jerez de la Frontera (Ca)	28	Arbequina	2006	7 × 6	238	Irrigated	Native	No	Clay-loam	8.3	0.18	4.0

branches (at least 2 cm diameter) were measured. The measurements were performed with a forestry calliper and rigid metallic metric tape. The biomass volume was calculated using the equation:

$$\mathrm{BV} = 1/3 \times \Pi \times \mathrm{h} \times (\mathrm{R}^2 + \mathrm{r}^2 + \mathrm{R} \times \mathrm{r}) \qquad (1)$$

where BV: biomass volume; h: height (m); R: largest diameter (m); r: smallest diameter (m).

Additionally, cores were collected from the trunk and branches of each variety using the Pressler borer to determine the wood density.

Collection of soil samples

Five soil samples were collected manually in random locations of each HUOG using a 4-cm-diameter Eijkelkamp core sampler to depths between 0 and 30 cm. The sample soil was mixed and homogenized, and five additional samples of unaltered soil were also collected to determine the bulk density using a special Eijkelkamp probe with a closed ring holder. The soil samples were transported to the laboratory and stored in a refrigerator at − 30 °C until analysis.

Laboratory study and analysis

Laboratory analysis

Soil samples were air dried, shredded, homogenized and sieved. The C content in the wood samples and organic C content in the soil samples were determined by dry combustion using an elemental analyzer (EA 3000 Eurovector SpA Milán, Italy). The values thus obtained were multiplied by a factor of 2 to calculate the organic matter content [21]. Texture was determined using a Bouyoucos densimeter. Carbonates were quantified using a Bernard calcimeter. The pH of the soil was measured at a 1:2.5 soil: water ratio.

Calculation of biomass and C stock in olive trees

The wood volume of each selected tree was calculated according to the previously obtained biometric measurements (length and diameter of the trunk and different branching categories). The measurements from the three trees selected in each plantation were averaged. Thus, the olive tree C stock was obtained using the equation:

$$\mathrm{CS} = \mathrm{C\ concentration} \times \mathrm{WD} \times \mathrm{WV} \qquad (2)$$

where CS: olive tree carbon stock; C: olive tree carbon (g kg^{-1}); WD: wood density (Mg m^{-3}); V: wood volume (m^3).

Determination of soil organic C stock

The soil organic C (SOC) stock at the sampled depth (0–30 cm) was calculated using the equation:

$$\mathrm{SOCS} = \mathrm{SOC\ concentration} \times \mathrm{BD} \times \mathrm{SD} \qquad (3)$$

where SOCS: soil organic carbon stock; SOC: soil organic carbon (g kg^{-1}); BD: bulk density (Mg m^{-3}); SD: soil depth (m). Bulk density was determined by the core method using a soil core for each plot and depth [22].

Determination of GHG emissions during farming operations in olive tree plantations

In the method used here, the applied GHG emission factors were expressed in terms of kg carbon equivalent (CE). The amount of GHG produced by each HUOG was determined from crop records for each plantation using the emission factors (EF) proposed in the scientific literature, particularly those by Lal [23] and extended by Agence de l'Environnement et de la Maîtrise de l'Énergie (ADEME) [24]. The specific EFs for the olive tree plantations were calculated according to energy data and by studying the hourly output of the different farming operations [23].

Determination of C balance and C sequestration rate in olive tree plantations

The annual rate of C stored in the biomass and soil at a depth of 0–30 cm must be determined to estimate the net C balance or C footprint in each plantation after subtracting the GHG emissions produced during farming operations.

The net flux of C (NFC), which is expressed as the annual C sequestration rate per hectare for each HUOG and is also known as the C footprint, was determined from C sequestration data determined through the olive plantation biomass, soil C storage and GHG emissions during farming operations (expressed in CE) using the following formula:

$$\begin{aligned} NFC = {} & C\ sequestration\ by\ the\ aboveground \\ & parts\ and\ roots + C\ sequestration\ by\ soil \\ & - C\ emissions (CE) during\ farming\ operations \end{aligned} \qquad (4)$$

Statistical analysis

Annual data for each variable were subjected to analysis of variance (ANOVA), using a randomized complete block design combined with the error term according to McIntosh [25]. Means were compared using Fisher's protected least significant difference (LSD) test at $P < 0.05$. LSDs for the different main effects were calculated using the appropriate standard error terms. The Statistix v. 9.0 [26] package was used for this purpose. Using different dasometric measurements obtained from the 22 olive HUOGs as well as information corresponding to the variety, date and plantation frame, different predictive models were tested to estimate the annual C sequestration rate by the olive tree plantation biomass.

Results

C content in olive tree plantations

C content in the biomass of olive tree plantations

The shoot/root biomass ratios obtained for the uprooted olive trees, once the leaves and branches below 2 cm in diameter were removed, were similar for Picual and Arbequina: 4.2 and 4.3, respectively (data not shown).

The percentages of C content in the trunk wood, different types of branches and roots in both varieties did not differ, recording an average percentage of 45.7 ± 0.6% (data not shown).

The average amount of C stored in the total biomass of the 22 HUOGs was 5.9 ± 4.3 Mg ha^{-1} (Table 2). In intensive plantations of similar age, C accumulation by the Picual variety was much higher than C sequestration by the Arbequina variety, at 5.4 and 3.1 Mg ha^{-1}, respectively. In hedgerow super-intensive plantations, only the Arbequina variety was present. The amount of C stored per hectare in these plantations was greater than the amount stored per hectare in intensive plantations of the same variety, at 6.7 and 3.1 Mg ha^{-1}, respectively. The C sequestration by the Arbequina variety hedgerow plantations was 20% higher than the C sequestration by Picual variety plantations.

In summary, conventional plantations older than 60 years with densities between 80 and 100 trees ha^{-1} are capable of sequestering over 15 Mg ha^{-1} C in their biomass (Tables 1 and 2). This quantity can be attained by 18-year-old intensive plantations, especially plantations of the Picual variety, with densities of approximately 200 trees ha^{-1}. Moreover, super-intensive hedgerow plantations of the Arbequina variety with an average age of 6 years presented C sequestration values between 7 and 8 Mg ha^{-1} (Tables 1 and 2).

Table 2. **Organic carbon stock in shoot, root, soil (0–30 cm) and total according to variety and number of olive trees ha^{-1}.**

HUOGs	Variety	Number of olive trees ha^{-1}	Carbon stock (Mg ha^{-1})			
			Shoot	Root	Soil	Total
1	Picual	204	7.1	1.7	34.25	43.1
2	Picual	83	8.3	2.8	21.80	32.8
3	Arbequina	1333	2.5	0.6	39.96	43.1
4	Arbequina	1975	4.8	1.1	32.05	38.0
5	Arbequina	1975	7.4	1.7	12.26	21.4
6	Arbequina	1975	7.1	1.7	33.22	42.0
7	Arbequina	286	1.0	0.2	17.35	18.6
8	Picual	208	0.7	0.2	30.21	31.1
9	Arbequina	286	1.2	0.3	28.98	30.5
10	Arbequina	1852	6.2	1.5	32.09	39.8
11	Picual	208	1.2	0.3	35.95	37.5
12	Picual	190	3.2	0.8	23.10	27.1
13	Picual	247	4.0	1.0	14.74	19.8
14	Picual	208	11.7	2.8	33.64	48.2
15	Picual	208	2.1	0.5	23.44	26.0
16	Arbequina	500	3.2	0.8	15.37	19.4
17	Picual	100	12.2	4.1	4.23	20.5
18	Arbequina	238	6.0	1.4	39.75	47.2
19	Arbequina	238	1.6	0.4	40.13	42.1
20	Arbequina	238	1.3	0.3	33.26	34.8
21	Picual	179	6.8	1.6	36.66	45.1
22	Arbequina	238	3.7	0.9	3.78	8.4

Note: HUOGs: Homogeneous unit olive groves.

Organic C content in the soils of olive tree plantations

Mean organic C value in soils was 26.1 ± 11 Mg ha^{-1} for the 0–30-cm depth horizon (Table 2). The mean percentage of organic C of the soil was 0.7%. In most cases, the soils of the olive plantation units presented low organic matter content at 1.4% in the upper layer (0–30 cm).

Total organic C content of olive tree plantations

The mean amount of C sequestered in olive tree plantations was 31.5 ± 11.4 Mg ha^{-1}; 17% of this amount corresponds to C stored in the biomass and 83% corresponds to organic C in the 0–30 cm soil depth (Table 2). However, although the amount of C in the soil was higher, the importance of C stored in the tree biomass should not be undervalued, because the C sequestration rate by trees is more stable and increases over time in relation to the growth of the plantation.

Annual C sequestration rate in olive tree plantations

The aforementioned annual C rates were calculated as follows: by dividing the amount of C accumulated in the biomass and soil by the age of the plantation (in years). The annual C sequestration rate is a key indicator used to obtain the C footprint, and it is required to assess the different farming practices conducted in the olive tree plantation and determine their effect on C sequestration and GHG emissions as well as to implement guidelines to improve C sequestration and mitigate GHG pollution by the agroecosystem.

The annual C sequestration rate in the olive tree plantations (biomass and soil) was recorded at 2.24 ± 2.2 Mg ha^{-1} yr^{-1} on average, and showed a high degree of variability. Regarding plantation system intensity (Table 3), the mean value obtained for the super-intensive plantations was significantly higher

Table 3. **Annual C sequestration rate in shoot, root and soil according to olive tree plantations.**

Olive tree plantations	Carbon sequestration rate (kg ha^{-1}yr^{-1})				
	Biomass			Soil	
	Shoot	Root	Total	(0–30 cm)	Total
Conventional	178 c	60 b	238 c	224 c	462 c
Intensive	438 b	104 b	542 b	1596 b	2138 b
Super-intensive	958 a	224 a	1182 a	3076 a	4258 a

Note: Within-treatment means followed by the same letter are not significantly different at $P \leq 0.05$ according to least significant difference.

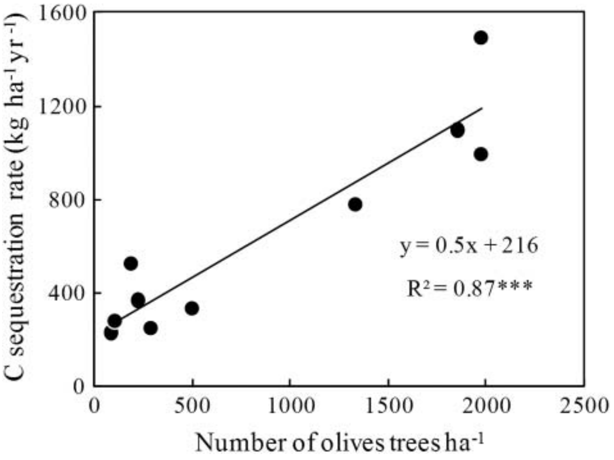

Figure 2. **Predictive model for determining the annual C sequestration rate as a function of the number of olive trees in the grove olives (traditional, intensive and super-**

(by nearly 2 times) compared with the intensive plantations, and the conventional plantations presented the lowest mean annual rates.

Estimation of a predictive model for determining C sequestration in olive tree biomass

Only the number of trees per ha, or plantation frame, fit a highly significant linear model defined by the equation (Figure 2):

$$y = 0.49x + 216(R^2 = 0.87^{***}) \quad (5)$$

This model can calculate the annual C sequestration rates from the variable *y* (expressed in terms of kg ha^{-1}) as a function of the number of olive trees per hectare in the plantation (independent variable *x*).

In addition, the data analysis showed differences in terms of C sequestration between the Picual and Arbequina varieties. In particular, the average annual C sequestration rate was 0.401 Mg ha^{-1} in intensive plantations of Picual and 0.374 Mg ha^{-1} in intensive plantations of Arbequina. As a result, a correction factor or coefficient of 1.1 was used in the model when analyzing the Picual variety, and the results obtained for the annual C sequestration rate in the equation must be multiplied by this factor (1.1) if the variety corresponds to Picual.

Similarly, data regarding the cultivation system and whether the plantations were irrigated or rainfed were analyzed. The average annual C sequestration rate was 0.303 Mg ha^{-1} in rainfed plantations and 0.374 Mg ha^{-1} in irrigated plantations. Thus, a correction factor or coefficient of 0.8 must be applied to the model when considering rainfed olive tree plantations, and the value obtained for the annual C sequestration rate in the equation must be multiplied by 0.8 when the model is applied to rainfed olive tree plantations.

Determination of GHG emissions from olive tree plantations

The mean total GHG value emitted during farming operations conducted in the studied plantations was 113 ± 54 kg CE ha^{-1}, with notable differences among plantations (Table 4).

Balance and carbon footprint in olive tree plantations

The average C balance and footprint for the studied plantations was 2.13 ± 2.18 Mg C ha^{-1} yr^{-1}, and high variability occurred between plantations, with values over 4 Mg C ha^{-1} yr^{-1} and, in one case, over 8 Mg C ha^{-1} yr^{-1} (data not shown). Regarding plantation intensity (Table 5), super-intensive plantations presented significant higher values compared with that of intensive and conventional plantations. In particular, the C balance was positive and C footprint negative in the three plantation systems, but the values obtained for super-intensive and intensive plantations were 9 and 5 times higher, respectively, compared with the values observed in conventional plantations.

Discussion

The average amount of C stored in the total biomass (1.35 Mg ha^{-1}) of the Arbequina variety in intensive plantations (286 number olive tree ha^{-1}) was lower than those obtained by Proietti et al [7]. These authors obtained an average of 1.473 Mg ha^{-1} yr^{-1} of C stored in the total biomass because the pruning and fruit yield were included.

The carbon storage may be increasing with the management practices as tillage system, use of organic residues, etc. [1,4]. The mean soil organic C stock (26.1 Mg ha^{-1}) was very similar to those obtained by Parras-Alcantara et al. [27] under long-term organic farming.

Few studies have assessed C sequestration rates and the C footprint of olive tree plantations, and most of these studies refer to plantations in Southern Spain and, to a lesser extent, Italy. Moreover, these works differ notably in their methods and results. Villalobos et al. [18] applied a model based on radiation use efficiency (RUE) to intensive olive tree plantations under irrigation in Southern Spain and obtained a potential C sequestration rate of 1.91 Mg C ha^{-1} yr^{-1}. This value is slightly lower than the average result obtained for the plantations included in this study (2.24 ± 2.22 Mg C ha^{-1} yr^{-1}) but similar to the annual C sequestration rate for intensive olive tree plantations (2.07 Mg C ha^{-1} yr^{-1}) (Table 3). The heterogeneity of the studied plantations (variety, planting age, etc.) makes it difficult to compare some factors between them. For this reason, these records are preliminary until the model is fed with the progressive incorporation of data. Carbon

Table 4. **Determination of GHG emissions expressed in equivalent carbon emission (kg CE) during farming operation according to homogeneous unit olive groves (HUOGs).**

	($kg\ CE\ ha^{-1}$)							
HUOGs	Tillage	Irrigation	Fertilizers	Herbicides	Fungicides	Insecticides	Harvest	Total
1	32.9	84.9	3.5	0.0	19.2	0.4	9.4	150.4
2	13.8	0	3.4	0.0	1.7	0.0	9.4	28.3
3	9.5	84.9	36.6	8.2	12.7	3.3	14.1	169.4
4	9.5	84.9	1.0	22.9	13.7	4.5	14.1	150.6
5	13.5	84.9	36.6	14.5	13.5	6.4	14.1	183.5
6	9.5	84.9	15.5	11.5	12.7	4.5	14.1	152.7
7	9.5	84.9	15.5	11.5	12.7	4.5	9.4	148.0
8	9.5	0	1.0	15.2	1.1	3.3	9.4	39.5
9	9.5	0	1.0	15.2	1.1	3.3	9.4	39.5
10	9.5	84.9	15.5	11.5	12.7	3.3	14.1	151.5
11	9.5	84.9	15.5	11.5	6.4	3.3	9.4	140.5
12	9.5	84.9	15.5	11.5	12.7	3.3	9.4	146.8
13	9.5	84.9	7.9	0.0	7.6	5.6	9.4	124.8
14	9.5	84.9	7.9	0.0	1.9	1.7	9.4	115.3
15	9.5	84.9	7.9	0.0	1.9	1.7	9.4	115.3
16	2.2	84.9	8.2	21.4	2.3	0.0	9.4	128.4
17	2.2	84.9	8.2	21.4	2.3	0.0	9.4	128.4
18	5.8	0	0.0	8.7	0.0	2.3	9.4	26.2
19	5.8	84.9	0.0	8.7	0.0	2.3	9.4	111.1
20	5.8	0	0.0	0.0	0.0	3.8	9.4	19.0
21	5.8	0	0.0	0.0	0.0	3.8	9.4	19.0
22	0	84.9	62.0	17.4	1.6	3.8	9.4	179.0

sequestration is based on an average annual rate of carbon storage of all the plantations. This model, certainly very general, has been included by the International Olive Council as a software tool for the design of a model to calculate the carbon footprint in the olive groves of the Mediterranean area [101].

Morales and Villalobos [28] applied the OLIVE-CW functional model to an intensive olive tree plantation of Arbequina by using growth and production rates along with CO_2 and H_2O flux measurements obtained by eddy covariance. The maximum C sequestration rate obtained in that study was 5.4 Mg C ha^{-1} yr^{-1}, which is twice the average value of the current results (2.24 ± 2.2 Mg C ha^{-1} yr^{-1}); however, the maximum values were closer, and their values did not surpass the current results. Regardless of the methodology used, the model used by these authors obtained maximum values by incorporating the shredded residues from light pruning into the soil. Olive grove cover-crop systems must be considered an efficient agronomic practice for soil carbon fixation [29,30]. In this paper, the soils belonging to many olive tree plantations presented negative annual accumulation rates of organic C in the soil, which indicates a loss of organic C in the soil over time as a result of poor soil management.

The authors' model is designed for two varieties (Picual and Arbequina), and an age range of planting between 7 and 58 years. The model includes traditional, intensive and super-intensive plantations and it has been established for the soil and climatic conditions of southern Spain. In this regard, it is clear that the model is limited although the progressive incorporation of data will allow the model to acquire a more and more general character, considering the importance of the two varieties and the studied area.

The high standard deviation confirms the marked variability in the C sequestration results and is a function of plantation age, plantation frame, variety, soil type and crop management. The oldest plantations, which were generally included in the traditional category, have accumulated higher quantities of C per hectare. In addition, in more recent plantations corresponding to intensive and super-intensive categories, plantation age also represents a key factor.

However, Nieto et al. [31] obtained values of potential C sequestration ranging from 0.5 to 0.6 Mg C ha^{-1} yr^{-1}, depending on soil properties by applying the RothC model, which considers C sinks and sources. These estimations are notably lower than the average results obtained in the current study for intensive and super-intensive plantations, but are similar to the values obtained in conventional plantations.

Table 5. **Balance and C footprint according to olive tree plantations.**

	Net C flux			
Olive tree plantations	C sequestration ($kg\ ha^{-1}yr^{-1}$)	GHG emissions (kg CE)	Balance ($kg\ ha^{-1}yr^{-1}$)	C footprint ($Mg\ ha^{-1}\ yr^{-1}$)
Conventional	462 c	78 b	384 c	0.38 c
Intensive	2138 b	90 b	2048 b	2.05 b
Super-intensive	4258 a	152 a	4107 a	4.10 a

Note: Within-treatment means followed by the same letter are not significantly different at $P \leq 0.05$ according to least significant difference.

Compared with the organic C content in soil from historical data provided by farmers, the values obtained in this study were negative in many of the plantations and consistent with a steady decrease over time of organic C in the soil. A positive difference was observed in other locations where the amount of organic C has increased significantly over time. This section of the study provides the least reliable values for the C balance and C footprint in olive tree plantations because the analysis provided by the farmers is relatively recent. The small time difference between the farmers' analysis and analysis conducted in this study makes it difficult to observe an increase in organic matter in soil resulting from improvements to soil management (cover crops, non-tillage, burial of pruning residues, etc.). Moreover, the soil management practices that are usually conducted in olive tree plantations have not been very favorable to increasing the amount of organic C stored in the soil.

The organic C in the soil is less stable, lower accumulation rates are observed and proper farming operations, including conservation tillage or retaining crop residue, increase C sequestration. However, intensive tillage and crop residue removal lead to negative rates and decreased amounts of organic C sequestered in the soil. Therefore, tree plantations present higher and more stable potential for C sequestration over time compared with plantations of herbaceous crops. A significant number of the studied plantations are capable of sequestering high amounts of C (over 80 Mg ha^{-1}) because they include good-quality and well-managed soil, they are well-developed and mature conventional plantations, or they are newer intensive plantations under irrigation with rapid biomass growth.

Regardless of the role of olive tree biomass for the annual C sequestration rate, which is directly related to the plantation density according to the authors' results and consistent with the results of Sofo et al. [16] in Southern Italy, the rate of C sequestration by the soil may play a significant role under proper management. According to Ramachandra Nair et al. [12], compared with systems without trees, agricultural systems based on trees sequester more C in the lower layers of the soil located near the trees, and higher organic C is observed in soils with greater tree density and increased lime and clay particles, which stabilize C. However, Lal [10] reported that the total amount of C sequestered in both the aboveground and underground parts of trees is affected by several factors, such as the region, plantation type and age, soil characteristics, etc. Overall, the difference between rainfed and irrigated agriculture in terms of C sequestration cannot be observed because its effect is masked by the age of the rainfed plantations, which are older. On average, the soil and aboveground portions are estimated to contain 60% and 30% of the total amount of C stored in tree plantations, respectively. These plantations have a significant potential for C sequestration over time and are more environmentally efficient C sinks for use in mitigating GHG emissions. The emissions values of the current study are relatively low compared with those of other tree plantations, and even with those of certain herbaceous plantations. The main factors contributing to the GHG emissions are irrigation and, in some cases, the use of fertilizers. These low levels of C emissions from farming operations are a result of the low inputs required for olive plantation growth, even in intensely irrigated plantations, and represent a positive aspect for the C balance and footprint because this results in higher net C flux and sequestration.

Numerous studies have addressed olive plantation soil management, including non-tillage, cover crop use (cover crops or native vegetation) and pruning residue incorporation, and they have demonstrated that these are efficient practices that might improve soil properties, reduce CO_2 emissions and increase the soil's ability to sequester C [29,31–33]. This effect has been confirmed in this study, in which olive plantations under proper soil management, including non-tillage, cover crop use and/or pruning residue incorporation, demonstrated positive C sequestration rates in the soil and produced the highest global C sequestration rates of the studied plantations.

Thus, it is clear that olive tree plantations represent an important potential for C sequestration. However, several questions must be clarified to provide a more realistic assessment of the impact of tree plantations and management practices on C sequestration. The authors tried to analyze in a timely manner the annual rate of carbon sequestration of different types of planting. It is clear that the future impact on carbon sequestration of different types of plantations will be different. However, the authors believe that this is a complex issue that is not clearly resolved; first, because intensive plantations with proper management and certain varieties of smaller size are lasting more years than expected. Also, often many superintensive plants undergo a transformation to intensive, uprooting a large number of trees whose branches are incorporated into the soil while the trunks of larger diameter are removed. Moreover, the data reported are referred to a specific time when all plantation trees were in production. It must be considered that this study has made a preliminary point, despite the remarkable efforts made in the field work. Without doubt, the authors' future work is designed to track the evolution of carbon sequestration in different types of plantations. Therefore, further research must be performed to assess all of the components of the C flux and the effects of environmental factors and crop management practices.

Conclusions

In this study, the potential of olive tree plantations for storing C in a stable manner has been confirmed and was especially evident in intensive plantations, thus highlighting the importance of these plantations for mitigating GHGs, as well as their role as CO_2 sinks. The net C balance in olive tree plantations presents a clearly positive impact on the life-cycle assessment of the product and improves estimates of the C footprint of olive oil as a final product.

A steady decrease in the amount of organic matter in the soil was observed in a large number of the studied olive plantations because of poor soil management, which has caused a negative accumulation of organic C over time. Improvements to soil management, such as conservation tillage, residue management and incorporation, cover crop use, etc., are recommended to progressively increase the accumulation of C in the soil and improve the C balance of olive plantation agrosystems over medium- and long-term periods.

By including the amount of C sequestered by olive tree plantations, the C footprint value calculated for the production and sale of olive oil could be reduced or even negative because the C sequestration rate of an olive plantation (biomass + soil) could surpass the emissions caused from farming operations and oil manufacturing. Ignoring the potential contribution of sequestered C in olive plantation biomass and soil when calculating the C footprint of olive oil is a serious methodological error that threatens the foundations of the life cycle of the product and C balance studies related to agricultural primary materials.

Extrapolating from the results of this study, the significance of the total area of olive tree plantations in the Mediterranean area, especially in Spain, which has over 2.5 million ha, demonstrates the worldwide importance that such plantations could have as significant CO_2 sinks and mitigating factors for GHG emissions caused by farming activities.

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