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Does olive cultivation sequester carbon?: Carbon balance along a C input gradient

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ABSTRACT

Currently, there are some initiatives aimed at transforming agriculture from being a source to a sink of greenhouse gases, mainly by encouraging combination of management practices that drive nature-based climate processes (NbCS) resulting in an increase in the stocks of soil and biomass organic carbon. Olive grove cultivation represents a key socio-economic and environmental asset for Mediterranean rural regions. Being a woody crop planted in an orchard fashion, the potential for organic carbon accumulation in the biomass and the soil is very high. In this study, farm, trees and soil carbon balances were analysed in 12 pairs of olive groves located in Southern Spain with different tree densities, age, varieties and irrigation regimens. One from each pair of the olive groves has applied (> 8 years) a combination of management practices that promote NbCS resulting in an increase in the entry of carbon, whereas the other comparable nearby olive grove has not implemented management practices that promote NbCS or C entries (non-NbCS). C balance at the farm level was mainly neutral or positive and averaged + 1.20 Mg C ha^{-1} y^{-1}. However, C balance in the NbCS olive groves was 5 times higher than that of the non-NbCS. The mean soil C balances were negative (−0.18 Mg C ha^{-1} y^{-1}; losing soil organic C) in the non-NbCS and positive (+1.48 Mg C $ha^{-1}y^{-1}$) in the NbCS olive groves thanks to the increase in the carbon entries due to the management practices which boost NbCS. This study highlights the important contribution of olive farming in mitigating climate change, which in turn would be an economic incentive for olive growers. Nonetheless, there is a high potential for improvement by implementing management practices which enhance nature-based processes such as the cultivation of temporary spontaneous cover crops and the application of shredded tree pruning and composted olive mill pomace and/or manure to the soil.

1. Introduction

Agricultural activities and land use change contribute to about 22 % (13 Gt CO_2-eq) of global greenhouse gas (GHG) emissions (Pathak et al., 2022). Consequently, a lot of attention is being paid to conceptual frameworks, such as the Nature-based Climate Solution (NbCS) concept, that encourage the implementation of a combination of management practices aimed at increasing carbon sequestration while reducing GHG. Carbon sequestration resulting from these NbCS are expected to become important tools to keep global warming below 2.0 °C (Griscom et al., 2017; Girardin et al., 2021).

In 2021, the European Commission started to promote carbon agriculture in the agricultural sector. The recent carbon farming initiative was derived from two important strategies from the European Green Deal (COM//640, 2019): the "*farm to fork strategy*" (COM//381, 2020) and the new period of the Common Agriculture Policy CAP 2023–2027 (Regulation (EU) (2021)/(2115)). The initiative aims to promote practices that store C in the soil and in the biomass in the long term, which has several positive effects; 1) the improvement of soil health which in turn promotes crop productivity; 2) net removal of atmospheric CO_2 and subsequent storage of carbon as organic carbon in biomass above or belowground and in agricultural soils; 3) the avoiding future emissions of CO_2 and other GHG as well as their reduction.

The carbon farming initiative could also contribute to boost new business models for farmers, consisting in economic incentives to take up additional farming practices with clear contribution to increasing SOC stocks. However, these incentives are result-based, and are therefore directly linked to reliable indicators of the increase in the stocks of SOC. In addition, farmers could benefit of a greater level of flexibility, as they can decide on their management strategies to achieve the targeted

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objective, taking into account the cost-effectiveness factor (Griscom et al., 2017), rather than following a rigid set of rules.

Nevertheless, the design of measurable indicators to establish incentives based on results is not so straightforward. There is great scientific uncertainty due to the absence of a precise methodology and information on the magnitude of the carbon sequestration potential of NbCS, since they differ depending on the agricultural system and its geography (Seddon et al., 2020).

Carbon farming includes a wide variety of NbCS, such as cover crops, improved rotations, incorporation of pruning residues from shredding, application of manure, restoration of peatlands, and expansion of agroforestry systems, among others (Creed et al., 2022; Mrunalini et al., 2022).

Agricultural systems that include trees, such as agroforestry or perennial tree-cropping systems, sequester carbon at a higher rate than other farming systems (Toensmeier, 2017) and hence might contribute more to the carbon farming initiative. This role may become even more important if farmers adopt land management and agronomic practices that maximize CO_2 sequestration, such as the use of cover crops and mulching of trees.

Olea europaea L. is the most important perennial crop grown in the Mediterranean basin, where occupies about 11.6 million hectares. Andalusia, the southernmost region of Spain, is the largest producer of olive oil in the world, and about 47 % of its agrarian utile area is devoted to olive groves (MAPA, 2020). There are various studies on olive groves that focus on the importance of certain management practices that lead to increased levels of organic carbon in the soil, which, in turn, leads to improved soil health, soil water retention, the increase in biodiversity and reduction of erosion, which would also help to mitigate climate change. For example, the incorporation of cover crops residues as green manure and tree pruning residues from shredding into the soil of olive groves are considered as promising sustainable management practices to reduce soil erosion risk (Alliaume et al., 2014; Francia Martínez et al., 2006; Gómez et al., 2009), while significantly increasing the entry of organic carbon in the soil (Gómez-Muñoz et al., 2014; Vicente-Vicente et al., 2016; Ramos et al., 2010; Torrús-Castillo et al., 2022). The application of composted olive mill pomace, which is the main byproduct of the olive oil industry (Sánchez-Monedero et al., 2008), has also been demonstrated to significantly contribute to the increase in SOC stocks in olive groves (García-Ruiz et al., 2012). Despite the proven potential of carbon sequestration and the co-benefits in ecosystems services by tree crops, there is not enough political support in implementing NbCS in woody crops, which undermines the potential for climate change mitigation of these crops. Some studies have analysed the CO_2 eq emission of the predominant olive groves cultivation models of mainly Italy (Proietti et al., 2014; Rinaldi et al., 2014), Spain (Fernández-Lobato et al., 2021a; Fernández-Lobato et al., 2021b) and Tunisia (Ben Abdallah et al., 2021; Fernández-Lobato et al., 2022). However, the focus of these studies has been the CO_2 eq emissions due to the farming operations and they have not considered the CO_2 accumulation as organic carbon in the soil or in other parts of the trees, that is, carbon farming.

Finally, as far as we are concerned, there are no studies that have provided information on all the flows of C within the olive groves. Additionally, flows of great importance in the carbon balance are ignored, such as those in cover crops, trees pruning residues and the application of composted olive mill pomace or manure, or organic carbon losses as a consequence of erosion or CO_2 emissions due to soil respiration, among others, which could overestimate or underestimate the results obtained from the balance of carbon. Therefore, it is essential to know and analyze in detail each of the flows that exist in the olive grove in order to implement the carbon farming initiative in the most realistic way.

We hypothesized that carbon balance is more positive in commercial olive groves that apply a combination of NbCS which represent an increase in soil organic carbon. With this hypothesis in mind, the objectives of this study were to assess for the annual carbon balance in the whole olive grove, including in the trees and in the soil, in commercial olive groves along a gradient of organic carbon inputs, and to delineate the contribution of the different input and output streams of C.

2. Materials and methods

2.1. Study sites and experimental design

12 pairs of olive groves in Western (Sevilla province) and Eastern Andalusia (provinces of Jaén and Granada) were selected (Fig. 1). The Mediterranean climate type in the area is semiarid, with long and very dry summers and precipitations concentrated in winter and early spring. Mean annual precipitation (MAP) ranges between 408 and 581 mm y^{-1}, with average values of 516 ± 56 mm y^{-1} for Eastern Andalusia and 482 ± 16 mm y^{-1} for Western Andalusia, and a mean annual temperature (MAT) between 13.7 and 17.2 °C, with average values of 15.6 ± 1.2 °C for Eastern Andalusia and 17.0 ± 0.2 °C for Western Andalusia (data from historical series 1991 – 2020). One of the olive groves of each pair correspond to an olive grove which has applied, at least during the last 8 years, a given combination of NbCS which represent an input of organic carbon. These management practices include: i) the implementation of spontaneous cover crops, ii) integration of livestock, iii) the application of composted olive mill pomace and/or manure, and iv) the residues of tree pruning via shredding.

The other olive grove of each pair has similar farm characteristics such as variety, age and plantation density (Table 1). However, in these olive groves, the aforementioned management practices are not carried out. In 6 of the pairs in Jaén and Granada (Eastern Andalusia), the variety was *picual*, whereas in the other 6 pairs located in Sevilla (Western Andalusia), it was *hojiblanca*. The selected olive groves include traditional, semi-intensive, intensive and super-intensive plantation frameworks, irrigated or rainfed and with trees between 25 and 200 years of age (Table 1).

2.2. Carbon input assessment

Annual carbon inputs in the olive groves include: C_{tree}, which is the annual rate of carbon accumulation in the permanent structures of the tree; C_{cc}, which is the annual carbon accumulation rate in both aerial and root biomass of the spontaneous cover crops; C_{pr}, which is the annual rate of accumulation of C in the tree pruning residues; C_{fw}, which is the annual rate of accumulation of C in firewood; C_{ext}, which is the annual application rate of C with the composted olive mill pomace, manure and other organic fertilizers; C_{leav}, which is the annual rate of accumulation of C in leaves and flowers that were estimated from the annual rate of fall of this material from the olive tree, together with the annual rate of accumulation of C in the fallen leaves during harvesting and in the leaves harvested with the olive fruit ($C_{leav\text{-}harv}$); C_{harv}, which is the annual rate of accumulation of C in the fruit collected during the harvest. C_{tree}, C_{pru}, C_{fw}, C_{leav} and C_{cc} are all assumed to be organic carbon which comes from the atmospheric CO_2 on the olive farm. Data is expressed as Mg C per hectare and per year.

2.2.1. Annual rate of olive tree C accumulation

The annual rate of olive tree C accumulation in the permanent structures of trees was calculated in between 5 and 7 representative trees per olive groves. The height and the largest and smallest diameters of the trunk and primary, secondary and tertiaries branches (except for those branches less than 2 cm) were measured. The measurements were performed with a forestry caliper and flexible metallic metric tape. The estimation of the volume of the olive trees was carried out by comparing each part of the olive tree to a geometric figure corresponding to a truncated cone (Velázquez-Martí et al., 2014) (Eq. (1)). The sum of all the volumes of the different sections (V_i) is an estimate of the tree biovolume (Eq. (2)).

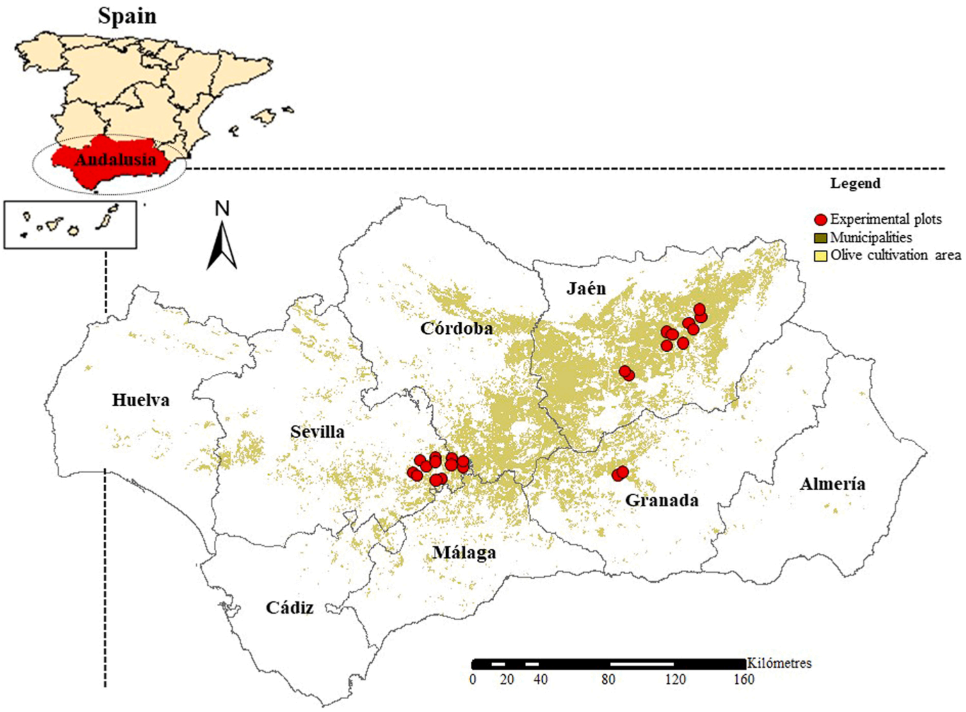

Fig. 1. Location of the studied commercial olive groves sites in Andalusia (Southern Spain).

$$V_i = \frac{1}{3} \times \Pi \times h \times \left(R^2 + r^2 + R \times r\right) \quad (1)$$

$$V_{tree} = \sum_{i=1}^{n} Vi \quad (2)$$

V_i is the volume of each section (cm^3); h is the height (cm); R is the largest diameter (cm); and r is the smallest diameter (cm).

To determine the wood density and the carbon content of different parts of trees (main trunk and primary and secondary branches), cylindrical pieces of each variety (*picual* and *hojiblanca*) were collected. The wood density was calculated based on the dry weight of the different cylindrical pieces over their fresh volume. In addition, root samples of olive trees just uprooted were collected in two farms not included in this study to determine the root organic carbon content. Root samples with a diameter lower and higher than 10 cm were dried, milled and carbon content was analysed in a CNHS elemental analyser (CNHS elemental analyser; Leco TruSpect Micro).

The aboveground dry biomass of the olive tree was obtained by multiplying the biovolume of the olive tree by the mean density of the wood. Root biomass was estimated using an aerial biomass/root biomass ratio of 4.2 ± 0.54 (López-Bellido et al., 2016). Knowing the aerial and root biomass, the total biomass of the olive tree was obtained, applying an expansive correction factor of 1.13 that compensated for the biomass of the canopy less than 2 cm (Ilarioni et al., 2013). Taking into account the dry biomass of olive trees and their number in one hectare, the amount of dry olive biomass per hectare was calculated.

From the total dry biomass of the tree and the organic carbon content of the different parts of the olive tree, the total organic carbon (kg C tree^{-1}) accumulated in the tree was determined. The stock of carbon of the olive trees (Mg C ha^{-1}) in each olive grove was calculated from the average stock of tree C (above and belowground) and the number of trees per hectare. In some cases, there were trees of different ages in the olive groves. In these cases, the tree biovolume in one hectare was the sum of the biovolume of each age type taking in to account the number of each type of tree per hectare.

The stock of tree carbon was divided by the tree ages to calculate the average annual rate of tree C accumulation (C_{tree}).

2.2.2. Annual rate of C in the tree pruning residues, olive leaves and flowers

Tree pruning residues of between 3 and 6 olive trees per olive grove were weighted in the field and a composite sample (typically higher than 10 kg) was transported to the lab. Water content (7 days at 50 °C in an oven) was measured and the proportion of leaves, twigs and branches recorded. Aliquots ($>$ 100 gr) of leaves, twigs and branches from the tree pruning were milled (blade mill $<$ 1 mm) and analysed for carbon content in a CNHS elemental analyser. The amount of carbon in the tree pruning residues was calculated from the dry amount collected from the tree pruning, the contribution of leaves, twigs and branches to the total weight and their carbon contents. Except for three of the olive groves where the tree pruning residues were burned in the field or harvested from the olive groves for energy production, tree pruning was typically carried out by shredding and applied on top of the soils. Tree pruning is usually performed each two or three years, although other tree pruning regimens (e.g., tree pruning at yearly basis) are possible. The amount of C in the tree pruning residues was divided by the tree pruning frequency as stated by the olive growers, to calculate the annual rate of C in the tree pruning (C_{pru}).

The amount of firewood produced in 3–6 trees of each of the olive groves was weighed in the field, and the aliquots transported to the laboratory to determine the water content, and the carbon content was analysed in a CNHS analyser once milled (blade mill $<$ 1 mm).

Carbon in the olive leaves and flowers falling down below the tree canopy in a year together with that fell down to the soil during harvest and that of the olive leaves which are harvested with the olive fruits ($C_{leave\text{-}harvest}$) were used as a proxy of the annual amount of CO_2 taken from the atmosphere and transformed into organic carbon in the olive leaves and flowers (C_{leave}). The amount of olive leaves and flowers which fell down the tree canopy were determined in field conditions. In the bottom canopy area of four traditional and four intensive olive groves, one or two plastic (30 cm × 30 cm × 12 cm) boxes were installed below the tree canopy and fixed on top of the soil. One box was installed when the trees were young (25–30 years old) and the canopy area was relatively low, and two boxes, when the trees were mature ($>$ 50 years) and the canopy area was relatively large. Each three months, for 12 months (from March to March of the following year), the material deposited in the boxes was collected and dried (50 °C during one week). The material consisted of olive leaves, flowers and very small aborted fruits. An aliquot of each type of material and for each of the three-month periods was milled (blade mill < 1 mm) to determine the carbon content (CNHS elemental analyser; Leco TruSpect Micro). The amount of carbon in the olive leaves and flowers that fell down annually was calculated from the amount (on dry basis) of material in the box, their carbon content, the area of the box and the area of the tree canopy. The canopy area of the olive trees with the boxes was measured using recent (2021) aerial images.

During the olive harvest, samples of the leaves and branches ($<$ 2 cm), that were raked or blown from the bales so as to bring the olives to the mill as clean as possible, were taken.

In some olive farms, two bales per olive tree were placed in a row of approximately eleven olive trees. Once the harvesting in that row was finished, regardless of the collection method, the two bales of each olive tree were dragged to the end of the row and two piles of leaves and twigs ($<$ 2 cm) made up the bales. In other cases, there was only one bale per olive tree, so when the shaking or vibrating was finished, they raked or blew the bale and took it to the next olive tree, thus generating a lot of leaves and branches for each olive tree. Once the piles were compiled, they were weighed with a dynamometer, and three representative samples of the leaves and branches were taken. In the laboratory, the samples were dried in an oven at 50 °C for 4 days to determine the percentage of dry mass of the leaves and branches collected.

Together with the olive fruit, some olive leaves are usually harvested ($C_{leav\text{-}harv}$). We assumed that this amount is 9.4 % (AGAPA, 2015) of the olive fruit, which is the average of what is produced in all the mills in Andalusia. Water and carbon contents of several aliquots of the harvested olive leaves were analysed.

2.2.3. Annual rate of C in the temporary spontaneous cover crops

The aboveground biomass of the temporary spontaneous cover crops (TSCC) was harvested in mid-March to the end of April and few days before been mowed or controlled by herbicides. Five 0.5 m × 0.5 m frames were randomly set in the area covered by TSCC in each of the olive groves, and the aboveground biomass was manually cut to ground level with grass shears and transported to the lab the same day (Gómez-Muñoz et al., 2014). The width of five strips was recorded in each of the olive groves where the TSCC occupied a band in the inter-row tree area.

Samples were dried at 50 °C for 4 days and weighed. The harvested aboveground dry biomass was assumed to be the aboveground net annual primary production for the period May 2020 to mid-April 2021, when sampling was carried out.

We assumed that 100 % of the area was covered by TSCC in olive groves where the TSCC covered the entire soil. For olives groves where the TSCC occupied a band of a given width of the inter-tree row area, the number of inter-tree rows in 100 m and the average width of the bands were considered to calculate the area covered in one hectare. The annual aboveground net primary production (kg DM ha^{-1} y^{-1}) was calculated from the harvested biomass in the frames and the area of 1 hectare covered by the TSCC. An aliquot of between 20 and 100 g of the dried harvested biomass was powdered with a hammer mill and carbon content analyzed in the CNHS elemental analyzer. The net annual biomass production of the root system of the TSCC was estimated by applying a root:aerial biomass ratio of 2.32. This value is the average obtained after running the RothC model in long term experimental temperate grassland sites where SOC was at stationary state (Poeplau, 2016). The amount of carbon in the root biomass was calculated from the root biomass, assuming an average root carbon content of 42.4 % (Ma et al., 2018).

2.2.4. Carbon in the olive fruits

The olive campaign usually starts in the middle of October till late January. Three bags of fifteen olives were taken from each olive grove. Each bag contained five olives from three randomly selected olive trees. In the laboratory, they were weighed fresh, and later, the stone was separated from the pulp, and both parts were weighed. Subsequently, they were dried in an oven for 4 days at 50 °C and analyzed for carbon in a CHNS elemental analyzer. The annual rate of C taken from the atmosphere which is accumulated in the olive fruit (C_{harv}) was calculated from the harvested olive fruit and water and carbon contents.

2.2.5. Off farm C inputs

The amount (fresh weight) of composted olive mill, manure, olive leaves from the olive mill and other sources of organic matter applied were recorded in each of the olive groves. Several aliquots of each were transported to the lab to determine the water content and carbon content, which was analysed in a CHNS elemental analyzer once dried and milled. Taking into account the fresh amount, the water and carbon contents and the frequency of application, the annual organic carbon input was calculated.

We assume that annual managed C inputs are that C that farmers can manage, and include: C_{pr}, C_{fw}, C_{cc}, C_{ext}, and $C_{leav\text{-}harv}$. The latter refers only to the leaves that are harvested with the olive fruit that end to the oil mill, but in three of the olive farms, part of this amount was incorporated back into the field without any treatment.

2.3. Olive farm carbon outputs

Carbon outputs were the carbon that exits the olive groves and include: i) carbon in the harvested olive fruits (C_{harv}) and leaves ($C_{leave\text{-}harv}$, ii) carbon in the firewood (C_{fw}), iii) carbon in the pruning residues (C_{pr}), only when it was burnt or taken out of the farm for energy production purposes, iv) organic carbon loss by soil erosion (C_{ero}), and v) soil CO_2 emission (C_{CO2}), taking into account both basal and organic carbon inputs-derived CO_2 emissions. C_{harv}, $C_{leave\text{-}harv}$, C_{fw} and C_{pr} were determined as above.

2.3.1. Carbon leaving the farm due to soil erosion

Soil erosion was estimated by the USLE/RUSLE equation (Wischmeier and Smith, 1978; Renard et al., 1997), applying a GIS-methodology. The wide variability of the farms selected for this study and the relatively large size of some of the farms (Tables 1A and 1B) made very difficult any empirical characterization of soil losses. For this reason, we applied a model that is widely supported in the literature, such as USLE/RUSLE. Soil losses (Mg ha^{-1} $year^{-1}$) were obtained at the plot level from Eq. (3):

$$A = R \text{ x } K \text{ x } LS \text{ x } C \text{ x } P \tag{3}$$

Where: R (MJ mm ha^{-1} h^{-1} $year^{-1}$) is the rainfall erosivity, calculated by the Fourier modified index (Arnoldus, 1997) from the average monthly rainfall of each plot; K (Mg MJ^{-1} mm^{-1} h^{-1}) by applying the RUSLE equation of Renard et al. (1997) from soil analyses (organic matter, clay, silt and very fine sand) and field data (structure) of three sampling points, which were all interpolated to the whole plot surface by the Voronoi polygons tool of QGIS. The LS-factor was obtained from the 5 m pixel size digital elevation model (DEM) of each plot by applying the equations of Moore and Wilson (1993) and Desmet and Govers (1996). To obtain the C-factor, a supervised classification (random forest) of two high-resolution aerial orthoimages with four colour bands (RGB + NIR, 0.5-pixel size) per plot was done following the methodology outlined by Peña-Barragán et al. (2004), using as training classes, three cover types (bare soil, canopy and cover crops, if present). To capture the temporal variability of cover crops, the classification was carried out over spring (Ma 2016) and summer (August 2017) images, and averaged to achieve a representative grid; the C-factor was obtained from the table for woody crops of Wischmeier and Smith (1978) employing the type, height and percentage of coverage of the representative grid. Finally, the P-factor considered the three subfactors of Wischmeier and Smith (1978): 1) contouring (P_C sub-factor), 2) contour

Table 1A
Relevant characteristics of the studied olive groves in Eastern Andalusia.

Olive farm	DEI-NbCS	DEI-nonNbCS	SP-NbCS	SP-nonNbCS	PV1-NbCS	PV1-nonNbCS	PV2-NbCS	PV2-nonNbCS	JT-NbCS	JT-nonNbCS	CC-NbCS	CC-nonNbCS
Province	Granada	Granada	Jaén	Jaén	Jaén	Jaén	Jaén	Jaén	Jaén	Jaén	Jaén	Jaén
Location (municipality)	Deifontes	Albolote	Úbeda	Úbeda	Villacarrillo	Villacarrillo	Villacarrillo	Villacarrillo	Pegalajar	Pegalajar	Úbeda	Baeza
Area (ha)	36.97	16.11	5.69	10.08	4.36	3.78	1.70	2.79	6.93	19.65	22.86	37.09
Plantation density (tree/ha)	156	143	100	100	83	83	100	100	150	83	70	140
Variety	Picual	Picual	Picual	Picual	Picual	Picual	Picual	Picual	Picual	Picual	Picual	Picual
Age (years)	25	27	37	30	200	200	40	30	50	85	100	78
Watter supply (m3/ha)	Rainfed	1000	1000	1550	800	Rainfed	1500	Rainfed	Rainfed	1000	Rainfed	Rainfed
Chemical fertilization (YES/NO)	NO	YES	NO	YES	NO	YES	YES	YES	NO	YES	YES	YES
Organic fertilization (YES/NO)	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES (ovejas)	NO
Tillage (typical number till pass)	1	2–3	NO	1	NO	2–3	NO	2–3	NO	2–3	NO	2–3
Spontaneous cover crops (YES/NO)	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO
Pruning residues (YES/NO)	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO (burned)	NO (CHP)	NO (burned)
Livestock (YES/NO)	NO	NO	YES (horses)	NO	NO	NO	NO	NO	YES (sheep)	NO	SÍ (sheep)	NO
Manure (YES/NO)	NO	NO	YES	NO	NO	NO	NO	NO	YES	NO	YES	NO
Olive mill pomace (YES/NO)	YES	NO	YES	NO	NO	NO	NO	NO	YES	NO	NO	NO
Incorporation of mill leaves (YES/NO)	NO	NO	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO
Pesticides (YES/NO)	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES	YES	YES
Herbicides (YES/NO)	NO	NO	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO
Soil type (WRB. 2014)	Calcic Cambisol	Calcic Leptosol	Vertic Cambisol	Vertic Cambisol	Vertic Cambisol	Vertic Cambisol	Peric Vertisol	Peric Vertisol	Calcic Leptosol	Calcic Cambisol	Chromic Vertisol	Calcic Fluvisol

Table 1B
Relevant characteristics of the study plots in Western Andalusia.

Olive farm	IS-NbCS	IS-nonNbCS	CH-NbCS	CH-nonNbCS	MR-NbCS	MR-nonNbCS	PA-NbCS	PA-nonNbCS	GA-NbCS	GA-nonNbCS	CR-NbCS	CR-nonNbCS
Province	Sevilla	Sevilla	Sevilla	Sevilla	Sevilla	Sevilla	Sevilla	Sevilla	Sevilla	Sevilla	Sevilla	Sevilla
Location (municipality)	Estepa	Estepa	Estepa	Estepa	Estepa	Estepa	Estepa	Estepa	Estepa	Estepa	Estepa	Estepa
Area (ha)	14.09	4.03	11.76	2.66	26.04	0.55	3.17	7.92	15.49	5.85	4.68	3.07
Plantation density (tree/ha)	126	100	260	236	285	357	238	333	110	160	100	56
Variety	Hojiblanca	Hojiblanca	Hojiblanca	Hojiblanca	Hojiblanca	Hojiblanca	Hojiblanca	Hojiblanca	Hojiblanca	Hojiblanca	Hojiblanca	Hojiblanca
Age (years)	25	28	27	30	25	38	25	35	35	38	50	28
Watter supply (m3/ha)	Rainfed	Rainfed	250	Rainfed	650	2650	4500	Rainfed	Rainfed	2800	Rainfed	Rainfed
Chemical fertilization (YES/NO)	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Organic fertilization (YES/NO)	NO	NO	NO	YES	NO	NO	NO	YES	YES	NO	NO	YES
Tillage (YES/NO)	NO	NO	NO	1–2	NO	NO	NO	1–2	1–2	1	NO	1–2
Spontaneous cover crops (YES/NO)	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO
Pruning residues (YES/NO)	YES	NO (burned)	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Livestock (YES/NO)	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Manure (YES/NO)	NO	NO	NO	YES	NO	NO	NO	NO	YES	NO	NO	YES
Olive mill pomace (YES/NO)	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Incorporation of mill leaves (YES/NO)	NO	NO	NO	NO	YES	NO	NO	NO	NO	NO	NO	NO
Pesticides (YES/NO)	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Herbicides (YES/NO)	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Soil type (WRB. 2014)	Calcic Regosol	Calcic Regosol	Calcic Regosol	Calcic Regosol	Calcic Luvisol	Calcic Luvisol	Calcic Cambisol	Calcic Cambisol	Calcic Cambisol	Calcic Cambisol	Calcic Regosol	Calcic Regosol

Strip-cropping (P_{SC} sub-factor) and 3) terracing (P_T sub-factor); which were calculated by means of GIS following the steps explained by Panagos et al. (2015a).

Ortoimages (RGB + NIR, 0.5-pixel size) and climatic (mean monthly rainfall from the 1970–2010 period) grids were downloaded from the Environmental Information Network of Andalusia (Red de Información Ambiental de Andalucía, REDIAM[1]), and the DEM (MDT05) from the Instituto Geográfico Nacional (IGN[2]) download service. Esri ArcMap® 10.5 and QGIS v.3.4.1 software were employed.

Carbon soil erosion (C_{ero}) was estimated from the annual loss of soil by erosion (Mg ha^{-1} y^{-1}) and the percentage of SOC, assuming the average enrichment ratio of the eroded SOC reported by López-Vicente et al. (2021) of 1 for olive groves with similar characteristics of our farms.

2.3.2. Soil CO_2 emission

Annual soil CO_2 emission was modeled for each farm following the RothC model. RothC (Coleman and Jenkinson, 2014) is a model that predicts, on a time scale that goes from months to hundreds of years, the changes that occur in the amount of SOC, as well as the amount of CO_2 emitted by the soil. In the RothC model, SOM is partitioned into four active compartments and into inert organic matter (IOM) that is resistant to decomposition. The four active compartments are: i) the organic carbon of the plant remains that decompose easily (DPM), ii) the organic carbon of the plant remains that decompose very slowly (RPM), iii) the organic carbon of the microbial biomass (BIO), and iv) the humified organic carbon (HUM). A fraction of both DPM and RPM decomposes by the action of bacteria and fungi, producing CO_2 that is released into the atmosphere and another fraction is transformed into BIO and HUM.

The input variables required by the model are: i) total organic carbon, ii) meteorological data (precipitation, evaporation and monthly temperature) of each olive grove obtained from the nearest meteorological station (2000–2020 mean data was used) and the monthly volume of irrigation water, which was added to the monthly precipitation, iii) depth of the soil layer sampled, which was the top 30 cm of soil, iv) percentage of the soil clay content of the top 30 cm of soil, v) the identification of the months within a year when the soil was covered or uncovered, and vi) months of application of the various sources of organic carbon (olive leaves falling down below the tree canopy, cover crops remains, composted olive mill pomace, tree pruning residues, manure or commercial organic carbon). Cover crops residues were applied on the soil in April, tree pruning residues in February, composted olive mill pomace and manure in February or in March and olive leaves throughout the year at different monthly rates.

The DPM/RPM of olive leaves, aboveground biomass of the cover crops and tree pruning residues, and composted olive mill pomace, were calculated after a 4-month lab experiment. The equivalent of 4 mg C g^{-1} of these sources of organic carbon were incubated with 100 gr of sandy loam and clay loam soils at an 80 % water holding capacity and the CO_2-derived was measured during different periods with the NaOH trap (Anderson et al., 1982). Cumulative CO_2 emitted from the added sources of organic carbon was fitted to a four-parameter double exponential equation and the labile and refractory carbon of each source of organic carbon were calculated for each of the two soil textures and averaged. DPM/RPM for olive leaves, aboveground cover crops and tree pruning residues and composted olive mill pomace averaged 0.17, 0.13, 0.15, 0.04, respectively. The DPM/RPM assigned to the root biomass of the TSCC was assumed to be the same than the aboveground biomass and the value of different manures was 0.5 (Jebari et al., 2021; Urbano-Terrón, 1992).

The model was run in equilibrium mode to establish the steady state of organic carbon in the soil, as well as the amount of carbon of the four compartments. Subsequently, RothC was executed in short-term mode, incorporating the management, climate and IOM of the analyzed olive grove.

2.4. Carbon balance

The farm level C balance was calculated after subtracting all the C output from all the C inputs following the equation (Eq.4):

$$\text{Carbon balance (CB)} = (C_{tree} + C_{pr} + C_{fw} + C_{leav} + C_{cc} + C_{harv} + C_{ext}) - (C_{pr} + C_{harv} + C_{leave\text{-}harv} + C_{fw} + C_{ero} + C_{CO2}) \quad (4)$$

The carbon balance of the trees (CBt) was assumed to be the annual rate of carbon accumulation in the permanent structure of the tree, whereas carbon balance in the soil (CBs) was calculated as: CBs = CB-CBt (Eq. 5).

2.5. Sensitivity analysis

The farm and soil C balances calculus described above involved many C fluxes some of which were measured, other estimated or modeled. To test how sensitive the farm and soil C balances were to the main C inflows and outflows, a model sensitivity analysis was conducted. For this analysis, the following assumed or measured C fluxes were increased by 50 %: annual net primary production of the TSCC (C_{cc}), amount of tree pruning (C_{pr}), amount of olive leaves falling down to the soil below the tree canopy (C_{leave}-$C_{leave\text{-}harv}$), soil erosion (C_{ero}), annual soil C-CO_2 emission predicted by the RothC (C_{CO2}), or decreased by 50 % in the case of the root-to-aerial ratio of the TSCC. Deviation (expressed as percentage of change) in the farm and soil C balances were calculated for each modified variable, site and for the NbCS and non-NbCS olive groves.

Soil CO_2 emissions depends on many inputs and is modeled by a highly complex and non-linear model such as RothC model used in this study. A sensitivity analysis was performed based in the simulation of the RothC inputs (TCSS residues, organic amendment, soil clay content, MAP, MAT, total soil organic carbon, IOM and DPM/ RPM) and the response variable (C_{CO2}). A multiple linear regression model was fitted from the simulated variables, obtaining the sensitivity coefficient β of RothC inputs. The coefficient β (expressed as so much per one) estimates how much the standard deviation of the result changes if there is a change of one standard deviation in the independent variable.

3. Results

3.1. Annual carbon inputs in olive groves

The mean amount of C which entered the studied olive groves annually averaged 4.7 Mg C ha^{-1}, but the variability was very high (Fig. 2). Values ranged from 3.2 Mg C ha^{-1} y^{-1}, in a traditional rainfed olive grove (PV1-nonNbCS), to 9.7 Mg C ha^{-1} y^{-1}, in a traditional irrigated olive grove (SP-NbCS), where the biomass of cover crops was the highest and where the whole olive mill pomace produced in the farms are composted and applied to the soil.

The mean annual C inputs in the olive farms which have applied a combination of NbCS (5.5 Mg C ha^{-1} y^{-1}) were 41 % higher than those in comparable olive farms (3.9 Mg C ha^{-1} y^{-1}) (Fig. 3), and differences were statistically significant ($p = 0.026$). On average, for the whole set of 24 olive farms, 75 % of the total annual C input which enters the olive groves came from the atmosphere, and there were significant differences ($p = 0.01$) between NbCS and non-NbCS olive groves (Fig. 3).

The highest contributions to the annual C inputs were that of the C which comes from the atmospheric CO_2 and is transformed to organic carbon in the fruit (stone plus pulp) (26 % on average; min and max of 12.4 % and 38.7 %, respectively) or in the olive leaves and flowers (22.0

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[1] https://www.juntadeandalucia.es/agriculturaypesca/ifapa/riaweb/web/inicio_estaciones

[2] http://centrodedescargas.cnig.es/CentroDescargas/index.jsp

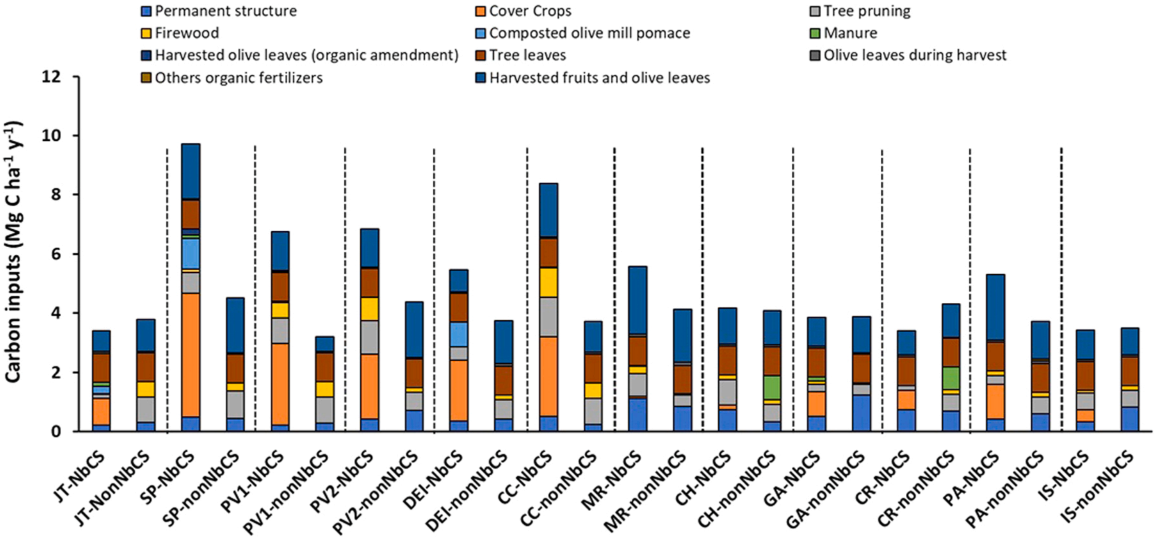

Fig. 2. Annual C input (Mg C ha^{-1} y^{-1}) in the 12 NbCS and compable non-NbCS pairs of olive groves.

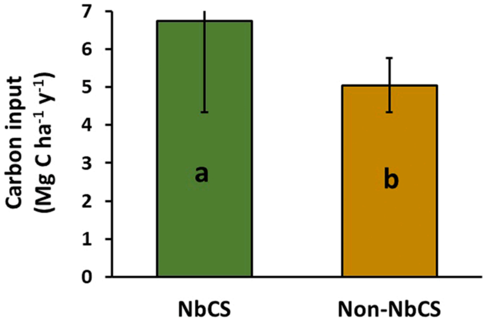

Fig. 3. Mean total C inputs in the whole set of NbCS and non-NbCS olive groves. Bars stands for standard deviation (n = 12). Different letters stand for significant differences (one-way ANOVA; α = 0.05).

% on average; min and max of 10.0 % and 30.3 %, respectively), which then ends up on the soil below the tree canopy after falling down (Fig. 4). Tree pruning residues (14.0 % on average, min and max of 3.6 % and 27.1 %, respectively) and the spontaneous cover crops (24.4 % on average; min and max of 0.91 % and 43.0 %, respectively) were also important C inputs. C in the permanent structures of the trees accounted on average for 12.5 % (min and max of 3.2 % and 32.0 %, respectively) of the annual input of C (Fig. 4). The annual rate of C input accumulated in the permanent structure of the trees for traditional olive groves was 0.5 Mg C ha^{-1} y^{-1}, which was 25 % lower than that for intensive olive groves (0.7 Mg C ha^{-1} y^{-1}) (Fig. 5). The annual rate of C allocation in the fruit in the intensive olive groves was 1.3 Mg C ha^{-1} y^{-1}, whereas values for the traditional olive groves were 1.1 Mg C ha^{-1} y^{-1} (Fig. 5). However, differences between the two were not significant (p = 0.27).

The annual rate of C inputs of the TSCC (aboveground plus belowground biomass of cover crops) averaged 1.5 Mg C ha^{-1} (min and max; 0.05 and 4.2 Mg C ha^{-1} y^{-1}, respectively), accounting for an average of 24.4 % of the annual C input in the olive groves with TSCC. However, the contribution of the annual C inputs due to TSCC differed significantly (p = 0.004) between the two models of TSCC layouts. Values when the whole olive grove was covered averaged 35.0 %, whereas the mean value was 13.0 % when the TSCC were distributed in strips in the inter-rows area.

External C inputs (e.g., manure or commercial organic fertilizers) in

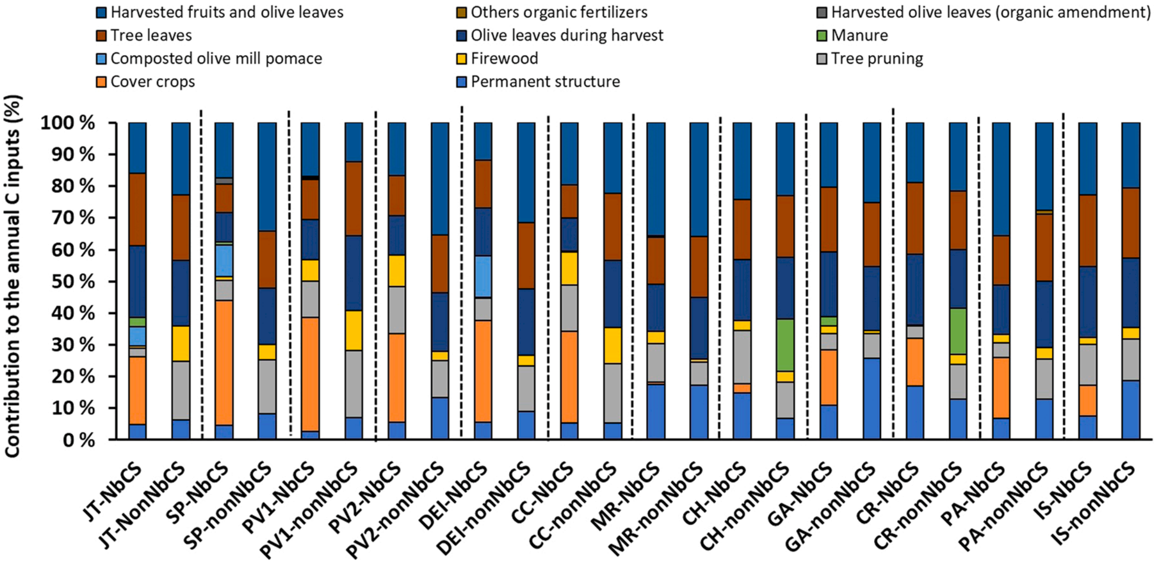

Fig. 4. Contribution of the different annual C inputs to the total C input in the 12 NbCS and comparable non-NbCS pairs of olive groves.

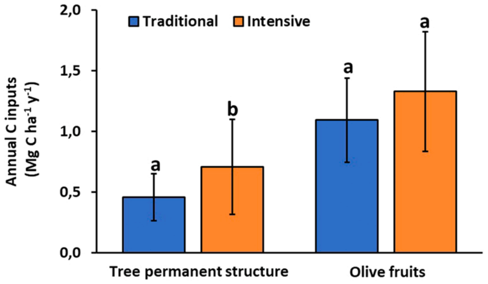

Fig. 5. Mean annual C input (Mg C ha^{-1} y^{-1}) which is accumulated in the permanent structure of the trees and in the olive fruits in the traditional and intensive olive groves. Bars stand for standard deviation and different letter mean significant differences between traditional and intensive olive groves.

the olive groves where off farm sources of organic carbon had been applied accounted on average for 24.9 % of the total annual C inputs (Fig. 4) for those olive farms which applied.

Overall, for the whole set of traditional olive groves, the mean annual carbon input was 4.8 Mg C ha^{-1} and was not significantly different from that of the intensive olive groves (4.5 Mg C ha^{-1} y^{-1}).

3.2. *Annual carbon outputs in olive groves*

On average, for the 24 Andalusian olive groves, 3.5 Mg C ha^{-1} left the olive groves annually (Fig. 6), although values ranged between 2.1 Mg ha^{-1} y^{-1} and 5.5 Mg ha^{-1} y^{-1} for a traditional rainfed olive grove with 200 year old trees (PV1-nonNbCS) and 100 year old traditional rainfed olive groves (CC-NbCS), respectively. Annual C outputs in the NbCS olive groves averaged 3.53 Mg C ha^{-1} and this was not significantly different from that of the non-NbCS average (3.51 Mg C ha^{-1} y^{-1}) (Fig. 6).

For the 24 olive groves, annual soil CO$_2$ emissions averaged 1.7 Mg C-CO$_2$ ha^{-1} y^{-1} accounting for 49.6 % of the total C output, without significant differences between the NbCS (1.73 Mg C-CO$_2$ ha^{-1}) and non-NbCS (1.72 Mg C-CO$_2$ ha^{-1}) olive groves (Fig. 6). C output with the harvest (olive fruit plus olive leaves collected during harvest) averaged 1.31 Mg C ha^{-1}y^{-1}, contributing to 37.6 % of the C outputs on average. The loss of carbon by soil erosion in the olive groves averaged 0.1 Mg C ha^{-1} y^{-1} for the whole set of 24 olive groves, accounting for an average of 3.3 % of the total C outputs (Fig. 6). Carbon losses by soil erosion were significantly higher ($p = 0.002$) in the non-NbCS (0.14 Mg C ha^{-1} y^{-1}) than in the NbCS (0.07 Mg C ha^{-1} y^{-1}).

3.3. *Olive farm, tree and soil C balances*

For the whole set of olive groves, C balance at farm level was positive (e.g., the olive grove was annually gaining carbon) except for three of them (JT-nonNbCS, CC-nonNbCSand IS-nonNbCS) and averaged + 1.2 Mg C ha^{-1} y^{-1} (Fig. 7). Variability was wide and ranged from − 2.0 Mg C ha^{-1} y^{-1} in a traditional rainfed olive grove (IS-non-NbCS) to + 5.4 Mg C ha^{-1} y^{-1} in an irrigated olive grove (SP-NbCS) with the highest C input due to TSCC and composted olive mill pomace application. Farm C balance for the NbCS olive groves averaged + 2.0 Mg C ha^{-1} y^{-1} and was significantly ($p < 0.05$) almost five times higher than that of the non-NbCS (+0.4 Mg C ha^{-1} y^{-1}) olive groves (Fig. 8). Farm C balance in the set of traditional olive groves was + 1.3 Mg C ha^{-1} y^{-1}, a 17 % higher than that of intensive olive groves, however, the differences were not significant.

C balance in the trees was always positive and averaged 0.54 Mg C ha^{-1} y^{-1} with a great variability; from + 0.21 to + 1.23 Mg C ha^{-1} y^{-1}, and without significant differences between NbCS (+0.51 Mg C ha^{-1} y^{-1}) and non-NbCS (+0.58 Mg C ha^{-1} y^{-1}) olive groves (Fig. 8).

On average, for the 24 olive groves, the soil gained C at an annual rate of 0.65 Mg C ha^{-1} y^{-1}. However, soil C balance of the NbCS olive groves averaged + 1.5 Mg C ha^{-1} y^{-1}, whereas the mean soil C balance of the non-NbCS was negative: − 0.2 Mg C ha^{-1} y^{-1} (Fig. 8). Differences between NbCS and non-NbCS olive groves were significant ($p = 0.005$).

The magnitude of the annual soil C balance was significantly related to the annual managed C inputs, with these being understood as the sum of C added with pruning residues, organic amendments and temporary spontaneous cover crops (Fig. 9).

3.4. *Sensitivity analysis of the carbon balances*

Fig. 10 shows the results of the sensibility analysis. The changes in the farm and soil C balances due to the 50 % increase of the major C inflows and outflows were very olive grove dependent and varied among the NbCS and nonNbCS olive farms. In addition, there were some outliers because a relatively low change in soil C balance in olive groves with very low positive or negative soil C balances, exerts a large percentage change.

As expected, farm and C balances of the nonNbCS farms were not sensible to the changes in the magnitude of annual net primary production of the TSCC (Fig. 10a) or the root-to-aerial biomass of the cover

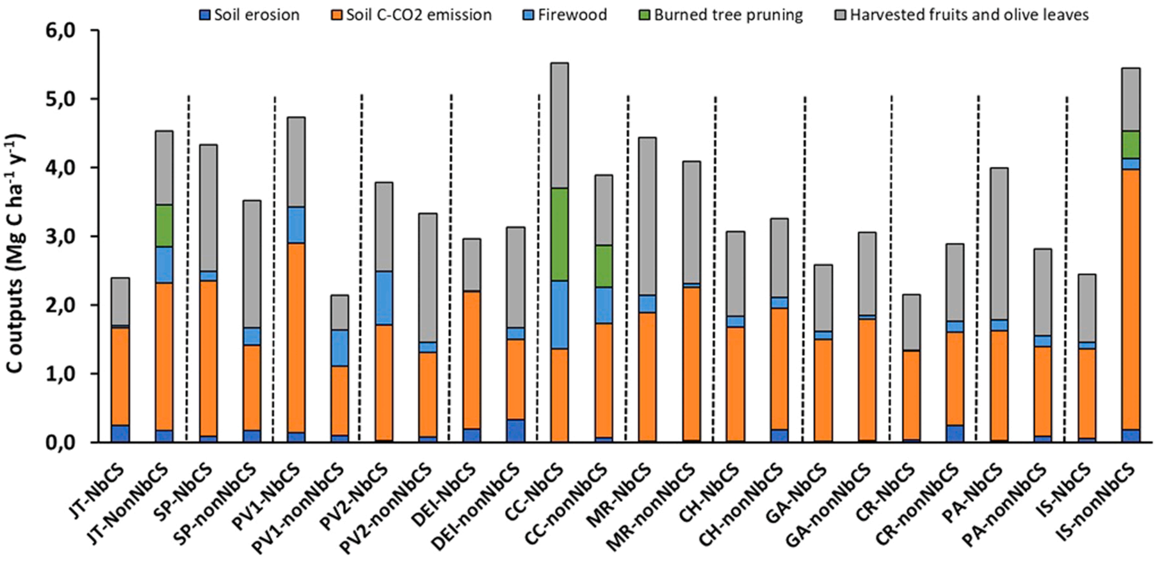

Fig. 6. Annual C outputs (Mg C ha^{-1} y^{-1}) in the 12 NbCS and compable non-NbCS pairs of olive groves.

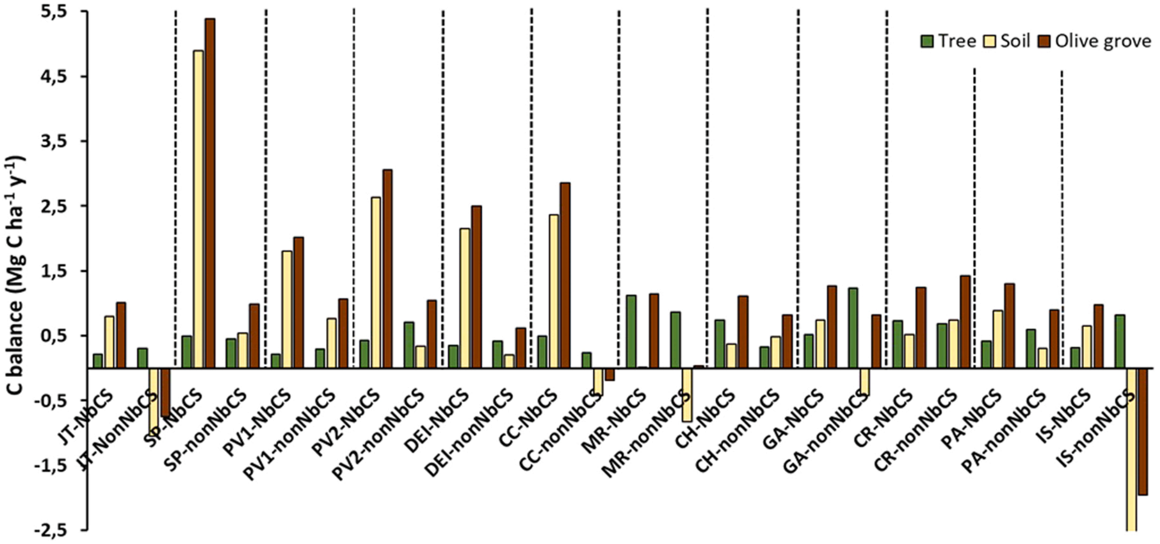

Fig. 7. Olive grove, tree and soil annual carbon balance (Mg C ha^{-1} y^{-1}) in the 12 NbCS and comparable non-NbCS pairs of olive groves.

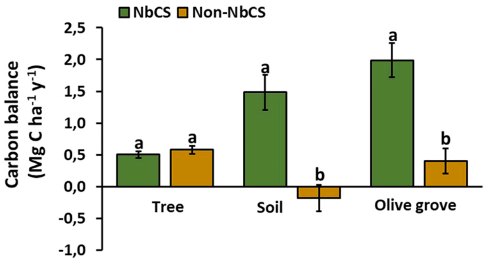

Fig. 8. Tree, soil and olive grove annual carbon balance (Mg C ha^{-1} y^{-1}) in NbCS and comparable non-NbCS olive groves. Bars stand for standard deviation, whereas different letter for significant differences between NbCS and non-NbCS olive groves.

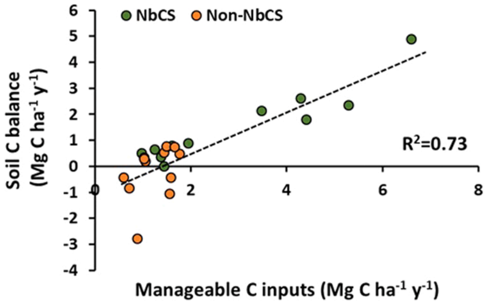

Fig. 9. Linear relationship between managed C inputs (Mg C ha^{-1} y^{-1}) and annual soil C balance (Mg C ha^{-1} y^{-1}) in the 24 olive groves (12 NbCS and 12 comparable non-NbCS olive groves). Linear relationship was significant ($P < 0.05$).

crops (10b). The farm C balances were less sensitive than the soil C balance because the annual accumulation of C in the permanent structure of the trees buffer changes in the soil C balance to some degree. Typically, the effects of the changes were greater in the nonNbCS olive farms than in the NbCS due to the fact that the C balances of the farm and soil of the latter were very low (negative or positive) and small changes in the balances result in a higher percentage change.

In the NbCS olive groves, and increase of 50 % of the annual net primary production of the TSCC provoked an average increase of 15.8 % and 29.1 % of the farm and soil C balances, respectively (Fig. 10a). A 50 % increase in the amount of tree pruning which are shredded and applied on top of the soil had little influence in both the farm and soil C balance of the NbCS olive farms (7.3 % and 11.6 %, respectively) (Fig. 10b). However, the effect of such increase was greater in the nonNbCS olive farms (20.2 % and 29.0 %, respectively) (Fig. 10b). The increase of the senescence olive leave C which fall down below the tree canopy had a great impact on the farm and soil C balances of both NbCS (26.2 % and 43 %, respectively) and nonNbCS (58 % and 84 %, respectively) (Fig. 10c). A 50 % of increase of the organic C applied which come from outside the farm (Fig. 10d) or on annual soil erosion (Fig. 10e) had minimal effects on farm and soil C balances in both types of olive farms (between 2.3 % and 15.8 % of change, respectively). A change in the annual soil CO_2 emission had profound changes in both the farm and soil C balances in NbCS and nonNbCS olive farms (between 53.9 % and 683 %) (Fig. 10f). Finally, a change in the root-to-shoot ratio had a medium effect on the farm and soil C balances as they changed by 19.9 % and 36.6 %, respectively in the NbCS olive farms.

4. Discussion

4.1. Annual olive tree atmospheric CO_2 removal is significant; the role of the permanent structure and olive leaves of the tree

The average value of the annual accumulation rate of organic carbon of the permanent structures of the olive trees in our study was 0.54 Mg C ha^{-1} yr^{-1}, being within the range of 0.25 and 1.25 Mg C ha^{-1} y^{-1} obtained by López-Bellido Garrido (2017) for 24 olive groves with different tree densities, age and varieties in Andalusia.

Moreover, the variability coefficient among our studied olive groves was as high as 50.8 % (range from 0.21 Mg C ha^{-1} y^{-1} to 1.24 Mg C ha^{-1} y^{-1}), mainly due to the fact that the annual rate of C accumulation (per hectare) in the permanent structures of the trees depends on tree age, number of trees per hectare and the tree pruning regimen (frequency and intensity), among others. Furthermore, the variability among trees from the same olive groves was relatively high (mean of 19.6 % of variability coefficient for the 24 olive groves) highlighting intra-olive grove differences due to tree specific pruning strategies, tree position in the farm and soil type, among others. As expected, values of C accumulation in trees of the silviculture forest species with between 300 and 600 trees per hectare, such as *P sylvestris* L. and *P pinaster* Ait., were higher and ranged between 1.2 and 1.3 Mg C ha^{-1} y^{-1} (Del Río et al., 2008). Nevertheless, the annual carbon stored in the permanent structures of the trees has a value equivalent to that of the carbon credits in the voluntary emission trading markets (COM//800, 2021), which are

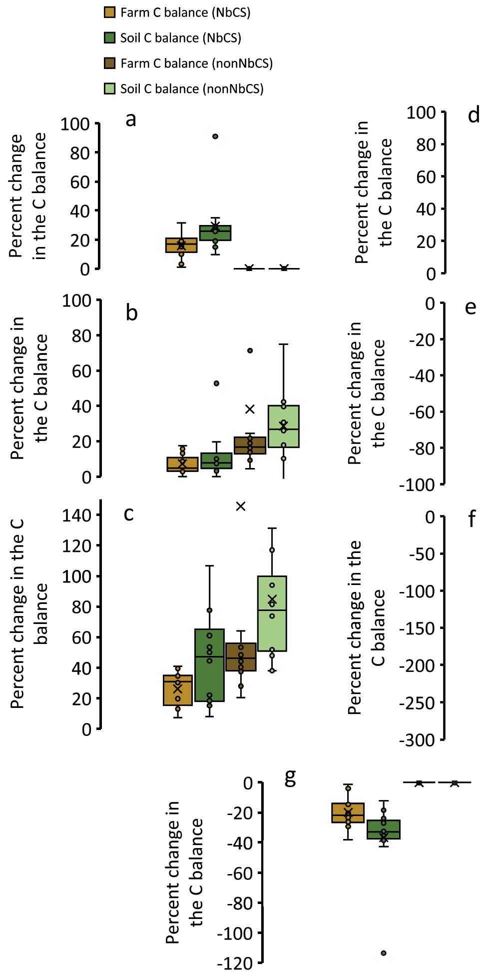

Fig. 10. Boxplot of the percentage of change in the farm and soil C balances of NbCS and nonNbCS olive groves due to a 50 % increase in the annual rate of (a) C in the TSCC, (b) shredded tree pruning C which is applied on top of the soil as a mulching, (c) olive leave C which fell down below the tree canopy, (d) C lost by soil erosion, (e) C entry with external inputs, (f) soil C emissions, and a 50 % decrease in the root-to-aerial ratio of the cover crop (g). Boundaries of the boxes closest to, and furthest from zero indicate the 25th and 75th percentiles, respectively. The X and the thick line within the box mark the median and average, respectively. Bars above and below the box indicate the 90th and 10th percentiles, respectively. Outliers are represented as black dots. Outliers, which were expected as a small change in the farm and soil C balances in olive groves with very low negative or positive values exerted a very large percentual change, are indicated. Note the different scales of some of the graphs.

considered by the European Commission, in regards to the *ex ante* mechanisms (i.e. the CAP payments for GAEC and echo-schemes), as the most effective tool for long-term carbon sequestration (COWI, 2021).

The annual rate of C accumulation in the permanent structure of the trees in traditional olive groves was 25 % lower than that of those in intensive olive groves, although differences were not significant ($p = 0.08$), despite the idea that relates the density of trees and the annual rate of accumulation of arboreal C. For example, López-Bellido et al. (2016), found that the higher the number of trees per hectare, the higher the amount of the annual atmospheric CO_2 fixation, at least until reaching the maximum tree crown canopy volume, which is typically used as an indicator of olive tree optimal productivity. In an intensive (330 tree per hectare) olive grove in Italy, Proietti et al. (2014) found an average of 1.47 Mg C ha^{-1} y^{-1} during 10 consecutive years in a 11-year old olive groves plantation, with a J type curve. Nevertheless, the annual C accumulation rate during year 9 and 10 averaged only 0.36 Mg C ha^{-1} y^{-1}, a figure similar to that of this study. Moreover, our data is not comparable in a straightforward manner with this because, during the first few years of olive growth establishment, CO_2 taken from the atmosphere is distributed preferentially in the permanent structures and the root system, but in mature olives trees, it is distributed, to a greater extent, to the leaves and fruits, and consequently, also in the tree pruning residues (Sofo et al., 2005). Thus, the extent to which organic carbon accumulated in the permanent tree structure of intensive and super intensive olive groves can function as a long-term (> 100 years) CO_2 sink, thereby contributing to carbon farming, will ultimately depend on the life span of these olive cropping models, which is currently under debate.

As a matter of fact, one of the main shortcomings stated by COWI (2021) for a suitable certification of carbon removal mechanisms is the period of time that sequestered carbon will remain on the farm. This is a difficult problem to deal with in a context as volatile as agriculture, especially in annual oil crops, whose management can quickly be changed if incentives in the voluntary carbon market drop. Soybean, rapeseed and sunflower are sown and harvested within the same twelve-month period, and their unharvested biomass and post-processes residues are typically applied on top of the soil, which then undergo the emission of CO_2 from most of the residue-C during decomposition. The CO_2 emitted into the atmosphere remains there for approximately 100 years so, to really offset these emissions, the carbon should be sequestered for the same period of time. Because more than 50 % of the 1,672, 996 ha of olive groves in Andalusia are older than 50 years (Junta de Andalucía, 2015), this crop shows a leading potential for carbon sequestration, even when compared to other permanent oil crops, such as oil palm, whose life span is around 25–30 years. However, if the recent trend of uprooting the older olive groves to establish super-intensive 20 year-life cycle orchards finally becomes a common practice, (Rodriguez-Cohard et al., 2020), this potential would become considerably lower.

Since almost two tons (1.98 Mg) per hectare of carbon dioxide was removed annually from the atmosphere and accumulated as organic carbon in the permanent structures of olive trees, and taking into account a price of 94.11 euros per ton in the CO_2 regulated market (date 04–14–2023), this could represent a positive economic impact of 186.3 € per hectare and year, even higher than the eco-scheme payments from the Common Agrarian Policy (MAPA, 2022). Assuming the same value for the 2,770,424 ha of olive groves in Spain and 1,672,996 in Andalusia (MAPA, 2021), this would be around 5.51 and 3.33 Mt CO_2 annually, respectively, which could be a noticeable fraction of the 42 Mt CO_2 that the EU plans to remove by carbon farming until 2030 (COM//800, 2021). Therefore, the permanent structures of the olive grove are currently playing a relevant role in the mitigation of greenhouse gas emissions, which in the CO_2 market is equivalent to 312 million € per year in the case of Andalusia.

As much as 0.96–0.97 Mg C ha^{-1} y^{-1} of mainly olive leaves, but also flowers and small aborted fruits were collected below the tree canopy in traditional and intensive olive groves, without significant differences between the two when expressed per hectare basis. Our values are similar to the range 0.93–0.98 found in a 60 year old traditional olive grove of Andalusia (Marañón-Jiménez et al., 2022). However, it is possible that some of the leaves, and therefore C, that have fallen down were due to abiotic (e.g., heat stress) or biotic (e.g., pest or diseases) stresses and not exclusively due to the annual natural senescence of olive leaves. In addition, the fate of this C is uncertain as some flowers, aborted fruit and olive leaves can feed wild animals without ending on the top of the soil. Nonetheless, the contribution of this C flow, which has been largely ignored or unaccounted for in other studies, to the annual CO_2 taken up by the trees and to the farm and C balances (sensitivity analysis) is rather significant and should be taken into account in future studies on C and CO_2 eq fluxes in woody crops. This typically unaccounted-for CO_2 flux might have resulted in an underestimation, not only of the annual CO_2 fixation by the olive trees, but also of the input of organic carbon to soil and in the farm and soil C balances.

Therefore, and due to the magnitude of this flux, more research is needed to characterize this C flux, which contributed on average to the 22.0 % of the C inputs of the studied olive groves.

Hence, considering C fluxes in fruits, permanent structures, leaves and flowers, the carbon dioxide removed from the atmosphere by trees that are not directly under the management decision of farmers accounts for more than half of the whole C input. This suggests a remarkable difference regarding annual crops in improving the climatic resilience of olive groves in a challenging socio-economical or environmental framework.

4.2. *The importance of the contribution of temporary spontaneous cover crops*

The contribution of the TSCC to the annual CO_2 taken from the atmosphere was rather significant, as olive grove productivity (Mg C ha^{-1} y^{-1}) in terms of atmospheric CO_2 fixation was increased by an average of 25 % in those olive groves with TSCC. However, the variability of this contribution was very high. Spatial variability among olive groves was expected as it is influenced by a complex array of interrelated factors, such as soil, climatic and landscape conditions (Taguas et al., 2017), the seedbank size and diversity, previous management of the TSCC (Gómez, 2017; Vicente-Vicente, 2017), the main TSCC layout model (Torrús-Castillo et al., 2022), the main dominant species of the TSCC communities (Cruz-Ramírez et al., 2012), and different herbivory pressure level (Guerrero-Casado et al., 2015).

The net primary production of the TSCC and the root-to-aerial ratio exerted a medium impact (a 50 % of change of both contribute to a percentage of change of between 15 % and 39 % of the farm and soil C balances of the NbCS olive farms) of both farm and soil C balances. Aerial net primary production of the TSCC in olive and other woody orchards is routinely analysed with sufficient accuracy mainly by the harvest method. However, the largest uncertainty in deriving CO_2 taken from the atmosphere or organic carbon entering the soil due to TSCC may originate in estimates of belowground C, including inputs from roots, exudates, and other root-derived organic material from root-turnover (root hairs and fine roots that are sloughed during the growing season). Though a large proportion of the net primary production of annual plants is allocated to belowground plant parts (Li et al., 2003), this amount is one of the most poorly understood and quantified of the C entry to the soil in terrestrial ecosystems. Quantifying the belowground C inputs of spontaneous or seeded cover crops in woody orchards remains a research priority and it is essential to gain accuracy in calculating the C footprint and C balance in these cropping systems.

The amount of organic carbon corresponding to the net primary production of the aerial part of the TSCC of the set of olive groves analyzed ranged from 0.02 to 1.12 Mg C ha^{-1} yr^{-1}, averaging 0.44 Mg C ha^{-1} yr^{-1}. There were significant differences when comparing the annual amount of organic carbon of the aerial biomass in relation to the TSCC layout model. Thus, the amount of organic carbon in the TSCC was higher in the olive groves where the TSCC covered the entire soil (0.71 Mg C ha^{-1} yr^{-1}) compared to those in which the TSCC were arranged in bands (0.17 Mg C ha^{-1} yr^{-1}). Therefore, by increasing the area covered, the potential contribution of TSCC could be enhanced further, as demonstrated by Torrús-Castillo et al. (2022). Additionally, the minimum width of 1 m for cover crops strips demanded by the GAEC nº 6 of the CAP cross-compliance (Regulation (EU), 2021/, 2115) may be insufficient to boost this mechanism of carbon sequestration. Our results suggest that, at least, a 40 % of herbaceous coverage should be considered for the area outside the canopy projection, as recommended by echo-schemes.

The TSCC implementation also delivers other ecosystem services co-benefits to farmers and society. TSCC can contribute significantly to the retention of nutrients in the olive groves (Torrús-Castillo et al., 2022), increase biodiversity (López-Vicente et al., 2021), increase the soil fertility and plant nutritional status (Scavo et al., 2022), reduce the losses of water and soil, and increase the levels of organic matter (Cerdà et al., 2021). Soil losses estimated by USLE/RUSLE averaged 4.36 ± 11.96 Mg ha^{-1} y^{-1} in NbCS olive groves and 17.90 ± 11.96 Mg ha^{-1} y^{-1} in the non-NbCS olive groves, with significant differences between both ($p = 0.002$). These data were relatively similar to those estimated from the European soil erosion map by the RUSLE 2015 (Panagos et al., 2015b), which has the highest resolution available for the study area (100 m-pixel size). The European soil erosion map yielded values of 9.80 ± 3.83 and 14.44 ± 7.79 Mg ha^{-1} y^{-1} in NbCS and non-NbCS olive groves, respectively. However, the differences were not significant ($p = 0.335$), probably due to the difficulty of accurately estimating the C-factor of the plots at 100 m-pixel size resolution. Our method, based in LiDAR technology and remote sensing, was adapted to work at the plot level, allowed a high resolution estimation of the TSCC (0.5 m-pixel size), which is not common in the application of the RUSLE model. This could certainly bring our data closer to those obtained, under very different conditions, in experimental settings. For instance, López-Vicente et al. (2021) reported soil losses of 9.2 and 14.3 Mg ha^{-1} y^{-1} in olive groves with and without spontaneous cover crops, respectively, in 8 × 60 m runoff plots from olive groves in Seville. The environmental conditions were very close to that of the Seville farms this study, so both data are rather consistent. Despite the relatively low influence of the annual C lost by soil erosion in the farm and soil C balances, the contribution of TSCC in olive groves to carbon farming is not only due to an increase in the SOC but also by reducing the C losses.

Some of these co-benefits of the TSCC might appeal to farmers (such as runoff and soil erosion reduction), making carbon farming more attractive; other co-benefits are public goods (such as biodiversity conservation, increase in olive groves water use efficiency and a reduction in the deterioration of rural infrastructure by excessive runoff). This aspect is so important that it is explicitly mentioned in the Commission proposal (COM//672, 2022) that is currently being debated in the European Parliament to establish a carbon removal certification mechanism: "*A carbon removal activity shall generate co-benefits for sustainable use and protection of water resources, pollution prevention and control and protection, and restoration of biodiversity and ecosystems*" (Article 7).

4.3. *Olive groves carbon balance: the higher the carbon inputs, the more positive the C balance*

The olive farm carbon balances for 21 out of the 24 olive groves were neutral or positive. As far as we are concerned, there are no studies that have accounted for the C balance taking into account the whole set of C annual fluxes of this study. López-Bellido et al. (2016), based on differences in the SOC stocks and on the C accumulated in the permanent structures of the trees, found that on average, C balance was always positive in 22 traditional, intensive and superintensive olive groves. In this study, the carbon balance for traditional olive groves was 0.38 Mg C ha^{-1} yr^{-1}, whereas that of the intensive groves averaged 2.05 Mg C ha^{-1} yr^{-1}. However, our results cannot be compared in a straightforward manner because, in that study, the olive groves with a clear negative SOC balance (e.g., loss of SOC) had the SOC balance set to zero and the soil fraction > 2 mm was not considered in their SOC calculations. In the study carried out by Fernández-Lobato et al. (2021b), the C balances of a short selection of traditional rainfed, traditional irrigated and intensive olive groves were negative (olive groves were losing carbon) and ranged from $-$ 0.24 to $-$ 0.61 kg C ha^{-1} y^{-1}. However, in this study, the olive groves did not implement spontaneous cover crops and the leaves, small twigs, flowers and fallen fruits of the olive trees, the application of organic amendments (e.g., oil mill manure, cattle manure and other commercial organic fertilizers) and organic carbon losses due to erosion were not considered.

The mean positive C balance of the 24 olive groves of + 1.20 Mg C ha^{-1} y^{-1} highlights the storage carbon in many of the olive farms of Andalusia on an annual basis, contributing to the climate change mitigation and thus, to the carbon farming initiative. In the three olive groves where farm C balances were negative, it was mainly due, but not exclusively, to the fact that tree pruning residues were burnt in the field or harvested for energy generation and TSCC were not implemented. The impacts on increasing the soil organic carbon levels of olive groves by tree pruning through shredding and applying the residues on top of the soil, typically as mulching, in the farm and soil C balance were significant (sensitivity analysis) and has already been demonstrated (Mairech et al., 2020; Nieto et al., 2010; Repullo et al., 2012). As mentioned above, tree pruning management, together with cover crops are key elements of the new 2023–2027 CAP recommendations that are quite supported by our results.

Despite the fact that the C balance at the farm level was mainly positive, soil C balances were negative (SOC loss) or neutral (unchanged SOC) in 9 out of the 24 olive groves. In these olive groves, spontaneous cover crops were not implemented or the TSCC biomass was very low (e.g., 0.05 kg C ha^{-1} y^{-1}) and there were no external (composted olive mill pomace or manure) C inputs. Therefore, in these olive groves, the annual carbon inputs into the soil did not compensate the carbon outputs mainly by soil CO_2 emission and soil erosion. This result reinforces the important role of the C of the residues of the mature spontaneous cover crops and the application of tree pruning by shredding residues on achieving positive soil carbon balance in olive groves. In the studied olive groves, more carbon input was generated internally (cover crops, tree pruning and composted olive mill pomace produced as byproducts from the harvested olive fruits) than imported (manure and soil amendments) and thus, most of the olive groves with negative SOC balances could have shifted to a positive SOC balance by increasing the on-farm C-inputs. Moreover, C balance in the olive groves averaged 1.99 Mg C ha^{-1} y^{-1} for the set of NbCS olive groves compared to the 0.40 Mg C ha^{-1} y^{-1} for non-NbCS olive groves. Thus, boosting the potential of on farm C entries, mainly by implementing full farm cover crops and the application of tree pruning, is a rather promising endeavor in terms of carbon-farming measures that are needed especially in crop farming with poor access to manure, which is the case in many areas of Andalusia.

The magnitude of the annual SOC balance was significantly related to the entry of organic carbon due to the various managements (e.g., implementation of spontaneous cover crops, application of the tree pruning residues once shredded, manure and composted olive mill pomace) as demonstrated in the sensitivity analysis. According to the significant relationship found in this study, about 1.2 Mg of organic carbon inputs per hectare would be needed annually for a neutral SOC balance, which can easily be achieved by combining the implementation of TSCC and the application of the tree pruning residues, both C fluxes produced within the olive groves. However, for the olive groves with a managed C input of less than 1.0 Mg C ha^{-1} y^{-1}, there was a high variability in the soil C balance (from −2.8 Mg C ha^{-1} y^{-1} to +0.88 Mg C ha^{-1} y^{-1}). This was because the soil CO_2 emission was highly dependent on SOC stocks and soil texture and also due to differences in the SOC losses by soil erosion depending on the mean slope, all of which differed in the olive groves. Typically, the higher the SOC, the higher the soil CO_2 emission, and therefore the more negative the soil C balance, especially when C inputs by management are lacking or are very low.

The emission of CO_2 from the soil was the C flux that most influenced both the carbon balances at the farm and at the soil levels. This C flux is usually not accounted for in most of the agricultural C footprint and C balance calculations, resulting in a significant underestimation of the soil and farm C outflows. The variable that most influenced CO_2 emissions from soils was soil total organic carbon ($\beta = \pm 78.75$), followed far by MAP ($\beta = \pm 16.14$), with the other parameters having little influence in the variability of C_{CO2} ($\beta < \pm 10$), and agrees well with the results of Janik et al. (2002). The analysis indicated that CO_2 emissions depend more on the content of total organic carbon of the soil, than on the agronomic characteristics of farms or the annual C entry to the soil, such as TSCC, tree pruning or organic amendments. This was expected as the annual entry of C in agricultural soil is very low (typically lower than 10 %) compared to the stocks of soil organic carbon.

5. Conclusion

The carbon balances at farm level of 21 of the 24 olive groves of Andalusia were positive, highlighting the contribution of this woody crop to climate change mitigation by taking atmospheric CO_2 and transforming it into organic carbon contained in the permanent structure of the tree and in the soil, which in turn would be an economic incentive for the olive growers. However, in 5 out of 24 olive groves, SOC balance was negative, and thus SOC losses, mainly by soil CO_2 emission, were not compensated by the organic carbon entry into the soil. Soil organic carbon balances in NbCS olive groves that have implemented management practices which enhance nature-based processes, such as cultivation of temporary spontaneous cover crops, application of tree pruning residues via shredding and composted olive mill pomace, were all positive whereas this was not the case for the non-NbCS olive groves. There was a clear relationship between the managed carbon entry and SOC balances, and an annual carbon input in the soil of about 1.2 Mg C ha^{-1} y^{-1} is needed to turn the negative C balance to neutral or positive.

This study demonstrates that most of the olive groves in Andalusia are contributing to climate change mitigation but their potential can be greatly enhanced by the implementation of management practices which boost nature-based processes.

CRediT authorship contribution statement

R. Garcia-Ruiz: Conceptualization, Methodology, Writing – original draft, Validation, Supervision. **J. Calero:** Conceptualization, Methodology, Validation, Supervision. **M. Torrús-Castillo:** Methodology, Investigation.

Declaration of Competing Interest

The authors declare that they have not known competing financial interest or personal relationship that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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