ENVIRONMENTAL RESEARCH
COMMUNICATIONS

INCLUSIVE PUBLISHING
TRUSTED SCIENCE

Part of the
ENVIRONMENTAL RESEARCH
SERIES

PURPOSE-LED
PUBLISHING™

PAPER • **OPEN ACCESS**

Can sustainable farming make olive groves carbon neutral? Empirical evidence from Mediterranean Portugal

To cite this article: Evangelina Pareja-Sánchez *et al* 2026 *Environ. Res. Commun.* **8** 055015

View the article online for updates and enhancements.

You may also like

- Carbon sequestration potential from sustainable management of arable land in the EU
Raül López i Losada, Mark V Brady, Fredrik Wilhelmsson et al.
- Soil carbon monitoring in forestry and arboriculture ecosystems of north-western Italy, according to a new orientation of agro-forestry production
Fabio Petrella and M Piazzi
- Global soil organic carbon sequestration potential under sustainable food systems and climate mitigation
Dianti Farhana Kamasela, Shinichiro Fujimori, Tomoko Hasegawa et al.

This content was downloaded from IP address 193.204.245.137 on 05/06/2026 at 10:35

Environmental Research Communications

Check for updates

OPEN ACCESS

RECEIVED
14 January 2026

REVISED
2 April 2026

ACCEPTED FOR PUBLICATION
30 April 2026

PUBLISHED
8 May 2026

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

PAPER

Can sustainable farming make olive groves carbon neutral? Empirical evidence from Mediterranean Portugal

Evangelina Pareja-Sánchez[1,*], **Sergio A Prats**[2,3], **Roberto García-Ruíz**[1], **Anna I De Luca**[4] and **José Muñoz-Rojas**[2,5]

[1] Research University Institute for Olive Groves and Olive Oil, University of Jaén, 23071 Jaén, Spain
[2] MED—Mediterranean Institute for Agriculture, Environment and Development & CHANGE—Global Change and Sustainability Institute, Évora, Portugal
[3] Misión Biológica de Galicia—National Spanish Research Council (MBG-CSIC), 36143 Salcedo, Pontevedra, Spain
[4] Department of Agriculture (AGRARIA), University Mediterranea of Reggio Calabria, Feo di Vito, 89122 Reggio Calabria RC, Italy
[5] Departamento de Paisagem, Ambiente e Ordenamento, Universidade de Évora, Pólo da Mitra, Ap. 94, 7006-554 Évora, Portugal
[*] Author to whom any correspondence should be addressed.

E-mail: epareja@ujaen.es

Keywords: carbon sequestration, carbon farming, soil carbon inputs, net co₂ emissions, olive groves, Mediterranean systems

Abstract

Agriculture contributes to greenhouse gas emissions while also offering potential as a carbon sink. However, the capacity of Mediterranean olive groves to offset their emissions remains poorly quantified, particularly as different cultivation models may vary substantially in their contributions to carbon sequestration and emissions, highlighting the need for comparative assessment to inform sustainable management and climate mitigation. This study assessed the carbon balance and footprint of six olive groves in Alentejo, Portugal, managed under integrated, organic, and biodynamic-organic systems. The groves were classified as low or high carbon input systems based on annual soil carbon inputs. Results showed that soil organic matter was more strongly influenced by carbon inputs than by the management system. High-input groves consistently exhibited a positive carbon balance (around +1.0 Mg C ha^{-1} yr^{-1}), whereas low-input groves showed more variable results, with values ranging from net carbon losses to modest gains. CO_2 emissions from agricultural operations were similar across systems (approximately 3200–3400 kg CO_2 eq ha^{-1} yr^{-1}), but net emissions were substantially lower in high-input groves (~140 kg CO_2 eq ha^{-1} yr^{-1}) compared to low-input groves (~1650 kg CO_2 eq ha^{-1} yr^{-1}). These findings highlight that increasing annual carbon inputs is more effective than changing management type for enhancing carbon sequestration and reducing net CO_2 emissions in olive groves, supporting carbon farming as a key strategy for climate change mitigation in Mediterranean agricultural systems.

1. Introduction

In recent decades, agriculture has been increasingly recognized as both a source of greenhouse gas emissions and a potential carbon sink, due to its capacity to capture and store carbon in soils. This dual role has been widely studied, highlighting the potential of agricultural systems to contribute to climate change mitigation (Lal 2004, Smith *et al* 2008, Plaza-Bonilla *et al* 2015, Pareja-Sánchez *et al* 2020). In Mediterranean regions, olive groves dominate agricultural landscapes and may play a particularly relevant role as carbon sinks when managed under practices that enhance soil organic carbon (SOC) (Castro *et al* 2008, Torrús-Castillo *et al* 2022).

Portugal, with approximately 400 000 hectares of olive cultivation, concentrates most of its production in the Alentejo region, which accounts for 51% of the country's olive-growing area (INE 2024). Over the last two decades, this semi-arid region has undergone rapid agricultural intensification, largely driven by irrigation expansion enabled by the Alqueva reservoir (Rodríguez Sousa *et al* 2021). This transformation has led to increased productivity but has also raised important environmental concerns, including soil degradation, erosion, and biodiversity loss (de Graaff *et al* 2010). These characteristics

© 2026 The Author(s). Published by IOP Publishing Ltd

make Alentejo a key region for assessing carbon dynamics in olive groves under intensified agricultural conditions.

In this context, carbon farming has emerged as a central strategy for climate change mitigation, promoting practices that enhance soil carbon sequestration and reduce greenhouse gas emissions (Smith *et al* 2008, Griscom *et al* 2017). In olive groves, these practices include cover cropping, incorporation of shredded pruning residues, application of olive mill compost (a by-product of the olive oil production process), and the use of organic fertilizers (Sánchez-Monedero *et al* 2008, García-Ruiz *et al* 2012). These practices not only increase SOC but also improve soil structure, reduce erosion, and enhance water retention, which is particularly relevant in Mediterranean environments. However, it is important to distinguish between carbon sequestration and carbon redistribution, as some practices involve internal carbon transfers rather than net atmospheric CO_2 removal (Chenu *et al* 2019, Don *et al* 2023).

Different cropping systems, including integrated, organic, and biodynamic-organic systems, represent contrasting approaches to soil and nutrient management. Integrated systems typically combine conventional practices with optimized input use, including synthetic fertilizers and mechanized management. Organic systems avoid synthetic inputs and rely on organic amendments and ecological processes to maintain soil fertility. Biodynamic-organic systems further incorporate holistic management practices, including compost preparations and enhanced biological interactions within the farm. These systems are often associated with improvements in soil health and environmental performance, although their effects on carbon sequestration and productivity remain context-dependent. Therefore, comparing these systems under real field conditions is essential to determine whether differences in certification schemes translate into meaningful differences in carbon balance.

Although intensification has improved yields, intensive systems are often associated with reduced soil carbon retention due to soil disturbance and limited ground cover (Gómez *et al* 2022). However, sustainable management practices such as reduced tillage can mitigate these effects and enhance carbon sequestration potential (Metzidakis *et al* 2008).

At the policy level, the European Union has set the objective of achieving climate neutrality by 2050, promoting carbon farming practices through initiatives such as the Green Deal and the Fit for 55 packages (European Commission 2021, Bäckstrand 2022). In this context, a 'carbon neutral' system is defined as one in which net CO_2 emissions are fully balanced by carbon sequestration within the system boundaries. These frameworks aim to incentivize carbon sequestration in agricultural soils and support the development of carbon markets, including potential carbon credits for farmers. In regions such as Alentejo, these policies may facilitate the transition toward more sustainable olive production systems.

In this context, understanding how carbon inputs translate into carbon balance requires an integrated assessment of carbon inputs and outputs at the farm level. The carbon balance of olive groves results from the interaction between carbon inputs and outputs, requiring an integrated assessment of both carbon accumulation and emissions. Carbon inputs include biomass production and organic amendments, while outputs involve soil respiration, decomposition, erosion, and emissions associated with agricultural operations (Fernández-Lobato *et al* 2021). Furthermore, soil carbon accumulation is not indefinite but reaches equilibrium over time, highlighting the importance of considering both short-term sequestration and long-term carbon dynamics (Chenu *et al* 2019).

However, despite the growing interest in carbon farming practices, there is still limited evidence on how different levels of annual carbon inputs influence both carbon balance and carbon footprint in Mediterranean olive groves. Most existing studies have focused either on soil carbon sequestration or on specific management systems, without integrating both perspectives. In particular, the relative importance of annual carbon inputs compared to management type in determining carbon balance remains insufficiently understood.

The main objective of this study is to evaluate the carbon balance of olive groves under different management systems (integrated, organic, and biodynamic-organic) and contrasting levels of carbon inputs. The specific objectives of this study are: (i) to evaluate differences in carbon inputs (e.g. biomass fixation, organic amendments) and outputs (e.g. respiration, harvest export, erosion) across olive groves; (ii) to quantify the annual biogenic carbon balance, assessing the carbon accumulated in tree biomass, in the soil system and the entire farm (tree + soil); and (iii) to determine the carbon footprint of these farms, evaluating to what extent carbon inputs offset CO_2 emissions derived from specific agricultural management activities (e.g. fertilization, irrigation, machinery use).

2. Materials and methods

The methodological approach was designed to assess differences in carbon balance and carbon footprint among olive groves under contrasting management systems and levels of annual carbon inputs.

2.1. Study sites and experimental design

Six olive groves were selected in the provinces of Évora (L1, H1, H2) and Beja (L2, L3, H3), both situated in the Alentejo region of Portugal (figure 1). These olive groves were selected to represent the range of management systems and annual carbon input levels in the region, enabling a comparative analysis under real farming conditions. The region is characterized by a Mediterranean climate with rainy mild winters and dry and warm summers (Csa in the Köppen classification), with an average annual temperature of between 15 and 25 °C across the region. During 2021–2022, rainfall was 423 mm (Évora) and 465 mm (Beja), while mean values varied between 587 mm and 555 mm, respectively, showing significant variability. All measurements and data collection were conducted over one agronomic year (2021–2022), ensuring consistency across all carbon flux estimations. The average annual potential evapotranspiration is 809 and 835 mm for Évora and Beja, respectively (IPMA 2024). The olive groves are predominantly established on soils derived from igneous rocks, such as granite, and metamorphic rocks like schist. These soils exhibit textures ranging from clay to loam (Rodríguez Sousa *et al* 2021, Muñoz-Rojas *et al* 2024).

Six experimental olive groves were selected based on a gradient of carbon inputs into the soil, categorized as follows: 0–3 Mg C ha^{-1} yr^{-1} (hereafter referred to as farms L1, L2, and L3) and >3 Mg C ha^{-1} yr^{-1} (H1, H2, and H3). These systems include super-intensive integrated plantations (L1), intensive plantations (H1), irrigated systems (L2, H2), and organic-biodynamic systems (L3, H3). Over the past eight years (except for farm L1, which has been cultivated for only two years), farmers have implemented a range of agronomic management practices based on agroecological approaches (De Luca *et al* 2023). All these practices contributed to increasing SOC inputs through varying degrees of spontaneous cover crop growth, manure application, livestock integration, and the incorporation of shredded olive pruning residues (table 1).

2.2. Assessment of the biogenic carbon inputs

For the evaluation of annual carbon inputs in olive groves, several key carbon fluxes are considered that contribute to carbon accumulation in different components of the olive groves. Below is a detailed description of these fluxes, which are expressed in Mg of carbon per hectare and year:

- C_{tree}; Annual rate of carbon accumulation within the permanent structures of the tree;
- $C_{litterfall}$; Annual carbon input to the soil from leaf and flower litterfall. These were estimated from the annual rate of olive leaves and flowers falling from the olive tree to the soil;
- $C_{pruning}$; Annual atmospheric CO_2 converted into organic carbon in the olive tree pruning residues;
- $C_{firewood}$; Annual atmospheric CO_2 which is converted into organic carbon within firewood produced from the olive trees;
- C_{cover}; Annual atmospheric CO_2 which is converted into organic carbon within the aerial and root biomass of spontaneous cover crops;
- $C_{leav\text{-}harv}$; Annual atmospheric CO_2 which is converted into organic carbon in the ligneous material and leaves harvested along with the fruit during harvest;
- C_{fruit}; Annual atmospheric CO_2 which is converted into organic carbon within the harvested olive fruits;
- $C_{org.fertilizer}$; Annual carbon input from the application of organic fertilizers including manure.

We assumed that C_{tree}, $C_{litterfall}$, $C_{leave\text{-}harv}$, $C_{pruning}$, $C_{firewood}$, C_{cover}, and C_{fruit} are derived from organic carbon captured from atmospheric CO_2 at the olive grove level.

For our analysis, annual managed C-inputs are defined as those carbon sources that farmers can directly control ($C_{pruning}$, $C_{firewood}$, C_{cover}, $C_{leav\text{-}harv}$ and $C_{org.fertilizer}$) (Ruiz-Carrasco *et al* 2026). The second to last category specifically refers to leaves collected during the olive harvest that are subsequently returned to the field without any additional processing, a process that we found to take place in three of

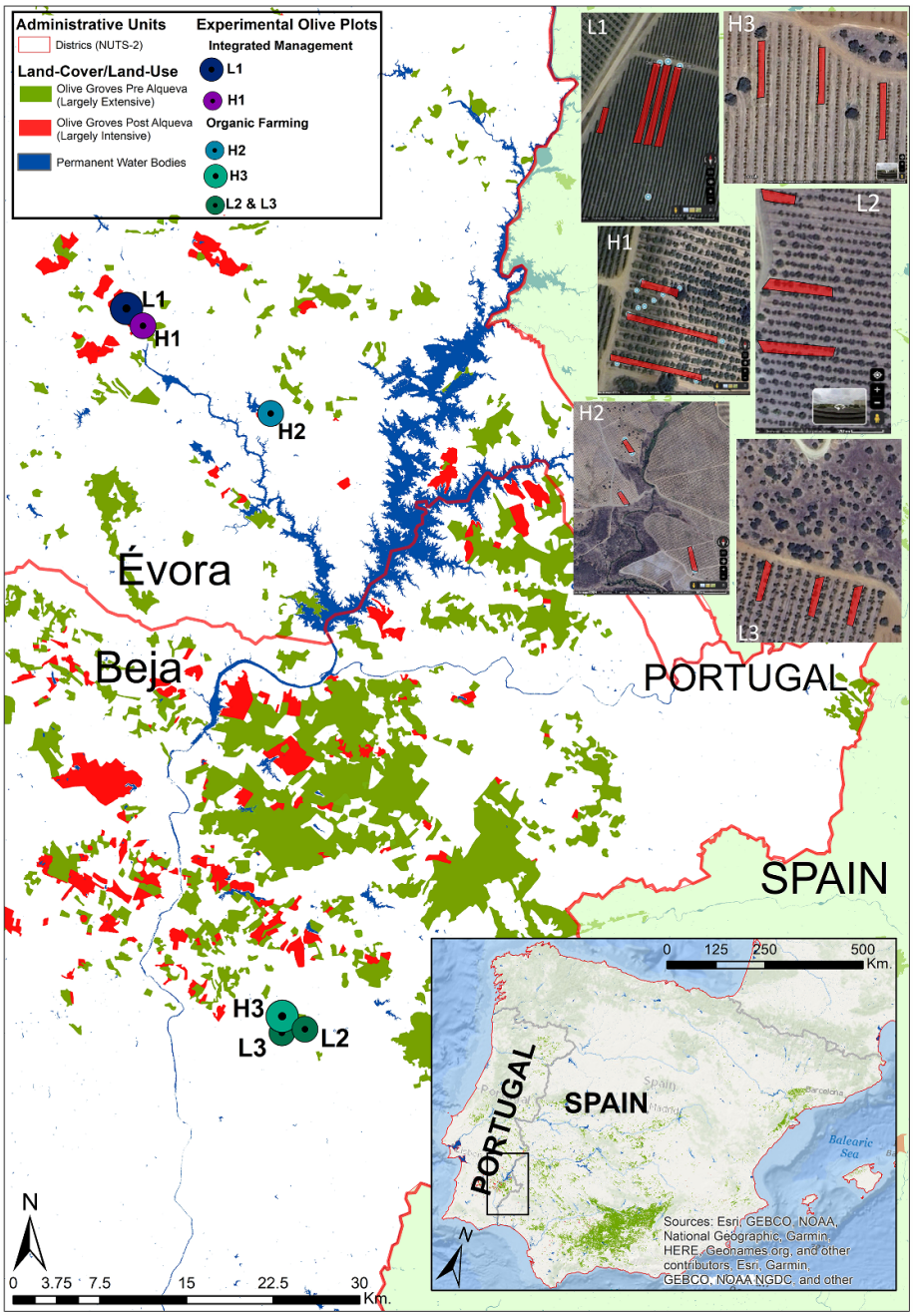

Figure 1. Location of Central Southern Alentejo (Portugal) and the study olive groves. Codes: low C-inputs: L1, L2, L3; high C-input farms: H1, H2, H3.

the studied olive groves. These manageable C-inputs represent carbon fluxes that can be directly influenced by farmers' management decisions and were used to evaluate the effect of agricultural practices on carbon balance.

Annual soil carbon inputs were estimated as the sum of all organic carbon fluxes entering the soil system, including litterfall ($C_{litterfall}$), pruning residues returned to the soil ($C_{pruning}$), spontaneous cover crop biomass (C_{cover}), and external organic amendments ($C_{org.fertilizer}$). These inputs were quantified through a combination of direct field measurements (e.g. biomass sampling, litter collection), laboratory analyses of carbon content using a CHNS elemental analyzer, and farmer-reported management data (e.g. pruning frequency, manure application rates).

Carbon inputs associated with harvested products (C_{fruit}, $C_{leav\text{-}harv}$, $C_{firewood}$) were not considered as soil inputs when removed from the system, but were included in the overall farm carbon balance. This approach allowed for a consistent estimation of soil carbon inputs across different management systems and carbon input levels.

Table 1. Basic agronomic characteristics of the experimental olive groves. Abbreviations: spontaneous cover crops (%), percentage of the surface covered by spontaneous cover crops; SOM, soil organic matter; SOC content, soil organic carbon stock; C, chemical fertilization; O, organic fertilization; M, manure.

Farm	Management	Tree density (trees ha^{-1})	Age (years)	Irrigation (Yes/No)	SOM (%)	SOC content (Mg SOC ha^{-1} top 30 cm)	Clay content (%)	Fertilization (C/O/M)	Tillage (Yes/No)	Herbicides (Yes/No)	Spontaneous cover crops (%)	Livestock (Yes/No)
L1	Integ	1925	2	Yes	2.20	25.95	21.89	C	No	Yes	18.7%	No
L2	Org	339	17	Yes	3.02	28.65	21.90	M	No (cutting)	No	24.1%	Yes (sheep)
L3	Org-biodyn.	104	100	No	2.18	23.21	23.3	No	No	No	100%	Yes (cow)
H1	Integ	272	13	Yes	2.31	24.89	21.11	C	No	Yes	19.3%	No
H2	Org	284	13	Yes	3.74	32.21	23.89	O	Yes (Plow)	No	15.9%	No
H3	Org-biodyn.	238	16	Yes	5.17	53.70	21.15	O, M	Yes (Plow)	No	37.1%	No

2.2.1. Annual rate of carbon accumulation in olive trees

The annual carbon accumulation in olive trees was assessed by analyzing a range of between 5 and 7 representative olive trees within each olive grove. Measurements undertaken included tree height, trunk diameter, and branch diameters. The estimation of tree volumes was performed using geometric methods following the methodology of Velázquez-Martí *et al* (2014). The total volume of the tree was calculated by summing the volumes of different sections (V_i) of the tree using the following equations (equations (1) and (2)):

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

$$V_{\text{tree}} = \sum_{i=1}^{n} V_i \tag{2}$$

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

To assess wood density and carbon content, samples from the main trunk and primary and secondary branches were analyzed using a CHNS elemental analyzer (LecoTruSpect Micro). The aboveground dry biomass of each olive tree was calculated by multiplying the biovolume by wood density values. Additionally, root biomass was estimated using an aerial-to-root biomass ratio of 4.2 ± 0.54 (López–Bellido *et al* 2016). The total organic carbon per tree (in kg C) and the carbon stock per hectare (in Mg C ha^{-1}) were subsequently calculated.

2.2.2. Annual rate of carbon in the olive leaves and flowers

To estimate the annual entry of atmospheric CO_2 which is converted into organic carbon of leaves and flowers ($C_{\text{litterfall}}$) 6 plastic boxes (30 cm × 20 cm × 15 cm) were placed in the ground below the canopy of olive groves to collect fallen leaves, flowers, and small aborted fruits. Over roughly a year period, the deposited litterfall material was collected at quarterly intervals and dried at 50 °C for one week. Aliquots from each collection period were milled to determine their carbon content using a CHNS elemental analyzer (LecoTruSpect Micro). The litterfall annual carbon amount was calculated based on the dry weight of the collected material, its carbon content, and the area of the boxes and tree canopy. The canopy area was measured using the most recent aerial images.

Along with the olive fruits (C_{fruit}), some olive leaves are generally harvested ($C_{\text{leav-harv}}$) that need to be equally discerned. Water and carbon contents of the olive leaf samples were also analyzed to understand their role in the overall carbon cycle.

2.2.3. Annual rate of carbon in the tree pruning residues

The evaluation of the annual carbon content in tree pruning residues involved collecting samples from 3 to 6 olive trees in each grove, which were then brought to the laboratory for analysis. The water content of these samples was measured following a drying period of 7 d at 50 °C in an oven. For analysis, portions greater than 100 g of tree pruning were ground to a size of less than 1 mm and assessed for their carbon concentration using a CHNS elemental analyzer. The total carbon content in the pruning residues was determined by calculating their dry weight alongside their corresponding carbon levels. Pruning of the trees generally involves shredding the material, which is then incorporated back into the soil every two to three years. However, other pruning intervals and destinations, such as its use to feed sheep and goats (as in L2), are often applied and were identified only through direct interviews with the farmers. Pruning residues were accounted for only in years when pruning operations occurred. In non-pruning years, no woody residues were generated and therefore no carbon input from pruning was considered in the annual carbon balance. The annual carbon rate from tree pruning (C_{pruning}) was computed by dividing the total carbon contents by the frequency of pruning as reported by each farmer. In addition, firewood produced by a range of 3–6 trees per olive grove was weighed in the field, and samples were then taken for analysis of water contents after milling the samples to less than 1 mm, followed by carbon content analysis conducted using a CHNS elemental analyzer (LecoTruSpect Micro).

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

The annual aboveground net primary production of spontaneous cover crop was quantified by collecting the aboveground biomass between May 2020 to mid-April 2021. In each olive grove, a total of 27 sampling frames (0.25 m × 0.25 m) were distributed across three representative zones: areas fully covered by spontaneous cover crops, tractor wheel tracks, and inter-row space between trees. Within

each frame, all aboveground biomass was manually clipped at ground level using grass shears and transported to the laboratory on the same day (Gómez-Muñoz *et al* 2014).

In groves where cover crops were arranged in strips within inter-row areas, the width of these vegetated bands was measured to estimate the total covered area per hectare based on the number of inter-row strips over a standardized length (100 m) and their average width. When spontaneous vegetation covered the entire soil surface, total coverage was assumed to be 100%.

All collected biomass samples were oven-dried at 50 °C for 4 d and then weighed to determine dry matter. Annual aboveground biomass production (kg dry matter ha^{-1} yr^{-1}) was estimated by scaling the measured biomass from the sampling frames to the total area occupied by spontaneous cover crops. Subsamples of 100 g of dried biomass were finely ground using a hammer mill, and their carbon concentration was determined with a CHNS elemental analyzer.

Belowground biomass production was estimated using a root-to-shoot ratio of 0.70, based on empirical data obtained from ten olive grove sites. The carbon content of root biomass was calculated from the estimated root mass, assuming an average carbon concentration of 42.4% (Ma *et al* 2018).

2.2.5. Carbon in the olive fruits

During the olive harvesting season (November 2021–January 2022), olive fruit samples were collected from each olive grove, consisting of nine bags containing five olive fruits each, randomly selected from nine distinct olive trees. In the laboratory, the olives were first weighed while fresh. Then, the stones were separated from the pulp, and the weights of both components were recorded. Following this, the fruits were dried in an oven at 50 °C for 4 d. Their carbon content was subsequently analyzed using a CHNS elemental analyzer. The annual carbon accumulation rate in the olive fruit, derived from atmospheric carbon (C_{fruit}), was calculated based on the harvested fruits along with their water and carbon contents.

2.2.6. Annual C-inputs from external sources

The quantities (fresh weight) and frequency of application of other sources of organic matter applied in each olive grove, such as manure, organic humic and fulvic acids, were documented. Samples of these materials were collected and transported to the laboratory to determine their water and carbon contents (CNH autoanalyzer) the annual organic carbon input was calculated for each organic matter considered.

2.3. Assessment of the annual biogenic carbon outputs

Annual C-outputs from the olive groves encompass several components of the olive farming system, including the previously described: C_{fruit} (annual carbon stored in the harvested olive fruits), $C_{leave\text{-}harv}$ (leaves associated with fruit harvesting), $C_{firewood}$ (carbon derived from firewood) and $C_{pruning}$ (carbon within pruning residues; but only if they are burned or removed to feed animals ($C_{feeeding.animals}$) or produce energy, as well as soil-related CO_2 emissions (C_{CO2s}) and C losses due to soil erosion ($C_{erosion}$).

2.3.1. Soil CO_2 emissions

The RothC model (Coleman and Jenkinson 1996) was applied to estimate annual soil CO_2 emissions for each grove, also allowing prediction of changes in SOC and CO_2 emissions over time. Key inputs required for this model include SOC, monthly meteorological data (precipitation, evaporation, temperature), soil depth (top 30 cm), soil clay content, periods of soil cover, and timing of organic carbon applications (e.g. olive leaves, cover crop residues). The labile to recalcitrant C ratio (DPM/RPM) required by the model for the different sources of organic carbon entering the soil was taken from Torrús-Castillo *et al* (2023), which was 0.17 for olive leaves, 0.13 for cover crop residues, 0.15 for tree pruning residues, and 0.5 for manure.

SOC content and stocks were assessed using soil samples collected over a 2 week period. At each farm, three random sampling points were selected, with soil collected from the 0–30 cm depth to provide three replicates per farm. The 0–30 cm soil depth was selected as it represents the most biologically active layer and is widely used in soil carbon studies. In addition, this depth is recommended by international protocols such as the IPCC guidelines and FAO methodologies for soil carbon assessment (IPCC 2006, FAO, ITPS 2018). Bulk density was determined from undisturbed cores collected at 0–5 cm and 15–20 cm depths using Kopecky cylinders (5 × 5 cm; 98.17 cm^3). In the laboratory, soils were air-dried, sieved (<2 mm), and separated into fine-earth and coarse fractions. SOC content (%) was quantified in finely ground subsamples using dichromate oxidation with sulfuric acid, following Anderson and Ingram (1993). SOC stocks (Mg SOC ha^{-1}) for the upper 30 cm of soil were calculated from SOC concentration, mean bulk density (derived from the two sampled depths and applied to the entire 0–30 cm

layer), and the proportion of fine earth. Soil organic matter (SOM) content was estimated from SOC values using the Van Bemmelen conversion factor (1.724), assuming an average carbon content of 58% in SOM (Nelson and Sommers 1996).

2.3.2. Annual organic carbon leaving the farm due to soil erosion

Soil erosion was monitored through one agronomic year (2021–2022) across six olive groves, through 3–4 sediment collection plots implemented in each grove. The sediment traps, designed to measure soil loss from laminar and rill erosion on plots of 200–300 m^2, were based on methods outlined by Rodríguez Sousa *et al* (2023). These traps, measuring 3–4 m in length, 1–2 m in width, and 40–50 cm in height, were constructed using geotextile fabric secured with wooden stakes and nails (Prats *et al* 2016). The traps allow water to filter through while sediment settles and accumulates. Installation of the sediment traps took place in May 2021, with sediment collection and analysis conducted monthly or after heavy rainfall events over the following year. Wet sediment was collected, weighed on-site, and later dried to calculate soil loss based on dry weight (de Graaff *et al* 2010, Gómez *et al* 2018). Total carbon leaving the farm due to soil erosion was calculated based on the annual erosion rate and the carbon content of the eroded sediments.

2.3.3. CO_2 equivalent emissions generated from farming operations

To determine carbon dioxide equivalent (CO_2-eq) emissions due to farm operations (C_{CO2m}), we employed the SimaPro 9.0 software, integrating the Agri-footprint 4.0, Ecoinvent 3.5, ELCD, and Industry data 2.0 databases. Emission factors were derived from these databases, following the ILCD 2011 Midpoint+ methodology. To calculate emissions, the ILCD 2011 Midpoint+ method (European Commission—JRC 2011) was applied, following approaches described by Desideri *et al* (2014) and Proietti *et al* (2014). The agronomic processes corresponding to the farming phase that were considered include soil management activities such as tillage, irrigation, fertilization, application of plant protection products, herbicide, harvesting and pruning of olive trees. Inputs considered in the analysis include the use of fuel, active ingredients of soil-applied products, polyethylene nets and energy consumption for irrigation.

The following assumptions were made: (i) olive planting phase: for olive trees over 25 years old, emissions from the planting phase were considered negligible (Salomone and Ioppolo 2012, Salomone *et al* 2015); (ii) irrigation: energy required for water use, generally sourced from the Portuguese electricity grid, but also photovoltaic or diesel-powered systems, in which case their impact was also considered as negligible; (iii) land use change: permanent crop cultivation land use was considered since olive cultivation was established in the region for longer than a century; (iv) burning of pruning residues: light pruning burns persist in limited cases, in spite of the strong regulations and permits, and the corresponding CO_2, CO emissions, which are widely recognized as part of the short carbon cycle, as well as other minor emissions, such as CH_4 and formaldehyde, were considered negligible and excluded from our analysis (Alves *et al* 2019); (v) transport distances: inputs transported to the olive groves were assumed to cover an average distance of 300 km, based on the proximity of the case study area to the main industrial cities and ports; (vi) infrastructure: emissions from buildings, warehouses, and related energy consumption were considered negligible for virgin olive oil production, as shown in other life cycle analyses (Salomone *et al* 2015); (vii) agricultural-related emissions: emissions to air, water, and soil were calculated following the IPCC Guidelines for National Greenhouse Gas Inventories (Aminetzah *et al* 2020), in alignment with the product environmental footprint category rules (European Commission 2017).

Primary data were collected through comprehensive surveys targeting all experimental olive groves included in this study. Data collection included open-ended questionnaires to capture observations that could not be obtained through quantitative surveys by themselves. Data validation included pre-testing with agricultural experts and academics, complemented by farm visits, official documents, scientific literature, and product datasheets. Positive values are observed as a consequence of CO_2 eq emissions from farm operations into the atmosphere.

2.4. Annual biogenic carbon balance and net CO_2 eq emission balances

The carbon accounting framework applied in this study is based on a mass balance approach, integrating all biogenic carbon inputs and outputs at the farm level to estimate carbon balance and net CO_2-equivalent emissions.

The biogenic carbon balance at the farm level was calculated by subtracting the total carbon outputs from the total carbon inputs, as synthesized in the following equation (equation (3)):

$$\begin{aligned}&\text{Biogenic carbon balance}\left(CB_{farm}\right)\\&=\left(\Sigma\left(C_{tree};C_{litterfall};C_{pruning};C_{firewood};C_{cover};C_{fruit};C_{org\cdot fertilizer}\right)\right.\\&\left.-\Sigma\left(C_{pruning};C_{fruit};C_{leave\text{-}harv};C_{firewood};C_{CO2s};C_{erosion}\right)\right).\end{aligned}\tag{3}$$

Biogenic carbon balance can also be calculated using the following equation (equation (4)):

$$CB_{farm}=CB_{soil}+CB_{tree}\tag{4}$$

where CB_{tree} represents the biogenic carbon balance of the trees (C_{tree}), the annual carbon accumulation within the permanent structure of olive trees, whereas CB_{soil} represents the biogenic carbon balance in all the other *C* compartments shown in equation (3). When the biogenic *C* balance is positive in the given compartment (tree, soil or farm), the compartment is gaining *C*, whereas when the balance is negative, the compartment is losing *C*.

The net CO_2 eq balance was calculated by combining the result of the biogenic *C* balance with the CO_2 eq emissions due to the farming operation (C_{CO2m}) as (equation (5)):

$$\text{Net } CO_2 \text{ eq } = C_{CO2m}-CB_{farm}\tag{5}$$

where CO_2 eq emissions refer to the emissions generated by the farming operation C_{CO2m}, and CB_{farm} is the result of the carbon balance converted into CO_2 (x 44/12).

2.5. Statistical analysis

The normality of the variances was assessed using the Shapiro–Wilk tests. For soil *C* balance, tree *C* balance, farm *C* balance and CO_2-eq emissions from farming operations, a one-way analysis of the variance was performed across carbon gradients. When significant statistical effects were found, means separation was carried out using a Tukey HSD test considering the 0.05 probability level. For net CO_2 emissions from soil and net CO_2 emissions at the olive grove level, a Kruskal Wallis test (*P*-values) was performed using total carbon gradients. When significant statistical effects were found, means separation was carried out using a multiple comparisons test considering a 0.05 probability value. The linear relationship between manageable annual C-input and annual soil carbon balance and manageable annual C-input and SOM and the statistical analyses were conducted using the statistical software STATISTICA v.10 (Stat Soft Inc.).

3. Results

3.1. Annual carbon inputs and outputs in olive groves

The six olive orchards showed marked differences in carbon inputs. The farms with the lowest C-inputs (L1–L3) showed an average of 2.71 Mg C ha^{-1} yr^{-1}, mainly originating from photosynthesis in the cover crops (1.28 Mg C ha^{-1} yr^{-1}) as well as from olive litterfall (0.35 Mg C ha^{-1} yr^{-1}). In contrast, farms H1–H3 showed higher annual C-inputs (4.58 Mg C ha^{-1} yr^{-1}), compared to L1–L3 farms (figure 2).

Carbon stored in the permanent structure of the trees contributed a small proportion of total inputs (<6% in high-input and 13% in low-input orchards). Spontaneous cover crops accounted for the dominant carbon pathway in both systems, constituting 51% of total inputs in the low orchards versus 42% in high orchards. External sources of organic carbon (manure, organic fertilizers) contributed similar proportions (6.9% in Low vs. 6.8% in high C-input farms) (figure 2).

The main C-output was soil CO_2 emissions, with higher values in high-input systems (−3.3 Mg C ha^{-1} yr^{-1}) than in low-input systems (−1.9 Mg C ha^{-1} yr^{-1}). Soil erosion contributes relatively little (between 3.1% and 3.4%) to biogenic C-outputs across olive farms (figure 2), while harvested olive fruits contributed between 38% and 11% of total C-outputs for high and low farms, respectively.

3.2. Tree, soil and the entire olive grove C balances

The annual biogenic carbon balance at the olive grove level was positive for both sets of olive groves (figure 3). The olive farm-level carbon balance was, on average, more than twice as high in High groves (+0.94 Mg C ha^{-1} yr^{-1}) compared to Low groves (+0.41 Mg C ha^{-1} yr^{-1}) (figure 3). The carbon

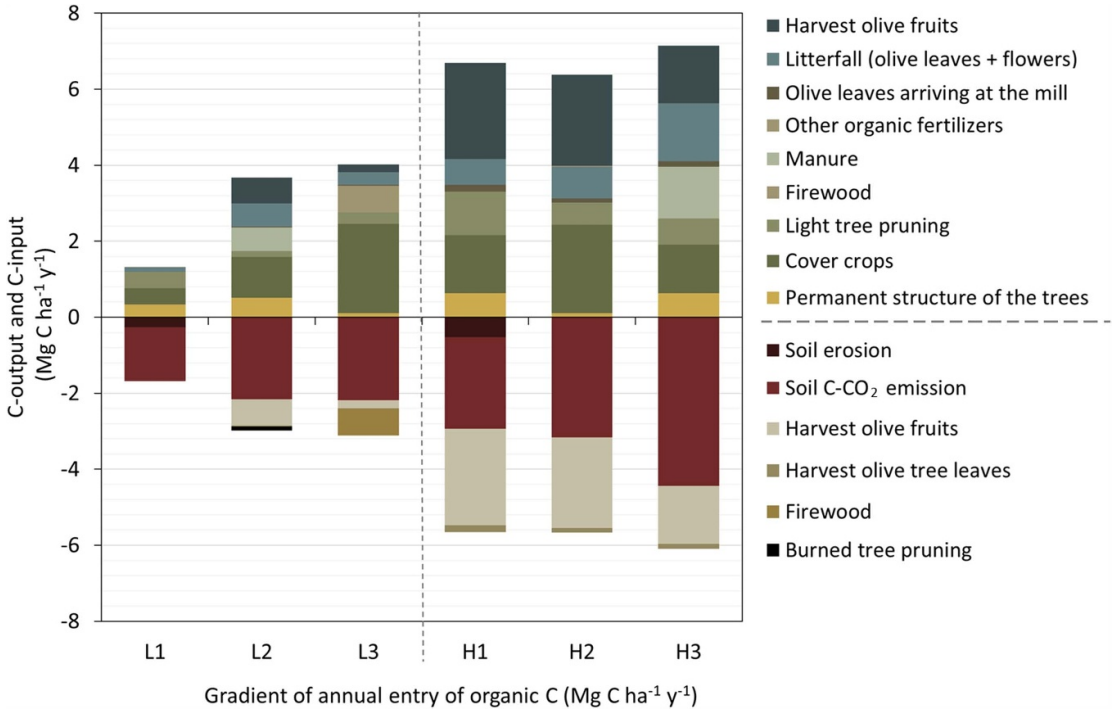

Figure 2. Annual C-input (positive data) and C-output (negative data) (Mg C ha^{-1} yr^{-1}) in low (0–3 Mg C ha^{-1} yr^{-1}) and high C-inputs (>3 Mg C ha^{-1} yr^{-1}) olive groves.

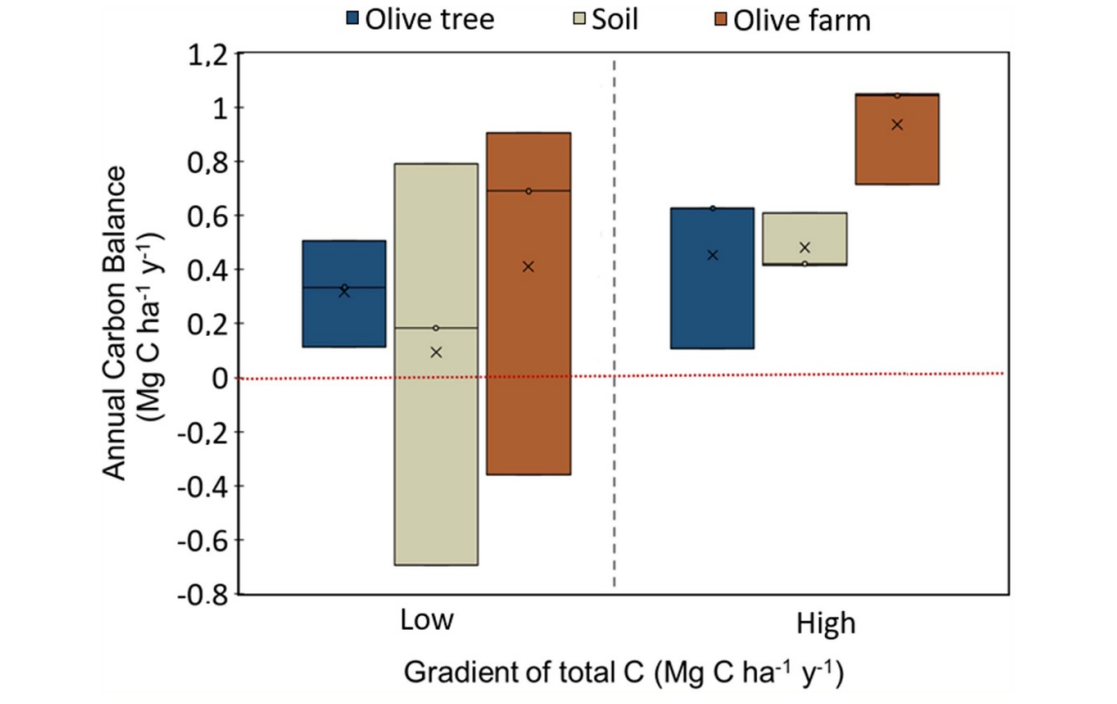

Figure 3. Boxplot of the olive tree, soil and olive farm annual carbon balances (Mg C ha^{-1} yr^{-1}) in the low and high olive groves. Boundaries of the boxes closest to, and furthest from zero indicate the 25th and 75th percentiles, respectively. The thin lines within the box mark the median and the *X* mark average values. Bars above and below the box indicate the 90th and 10th percentiles, respectively.

balance of the olive trees was positive. Although High groves showed a greater carbon gain than Low groves, the differences between groups were not statistically significant. Similarly, soil carbon balance was higher in High olive groves (+0.48 Mg C ha^{-1} yr^{-1}) than in Low groves (+0.09 Mg C ha^{-1} yr^{-1}). However, these differences were not statistically significant (figure 3).

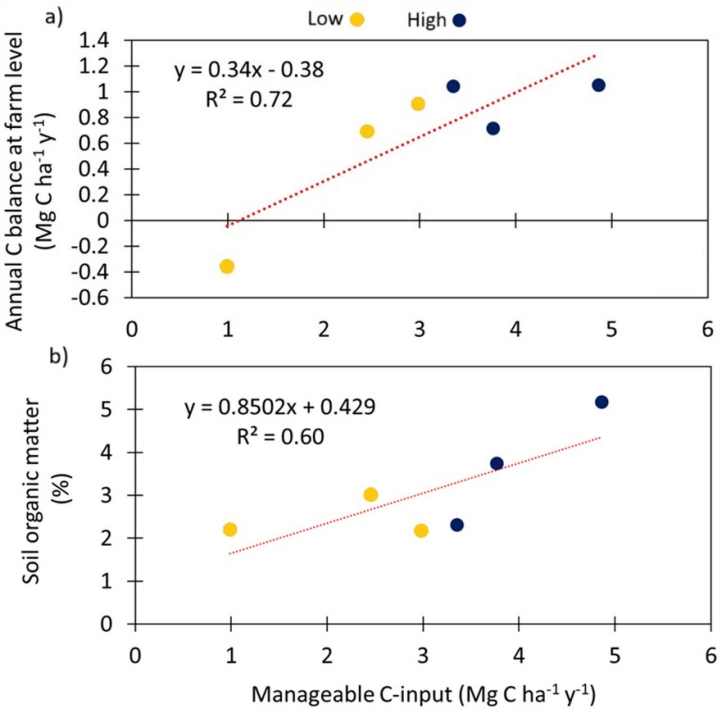

Figure 4. Linear relationship between manageable C-input (Mg C ha^{-1} yr^{-1}) and annual C balance (Mg C ha^{-1} yr^{-1}) (a) and manageable *C* input (Mg C ha^{-1} yr^{-1}) and soil organic matter (%) (b) in the 6 olive groves. Linear relationship was considered significant ($P < 0.05$).

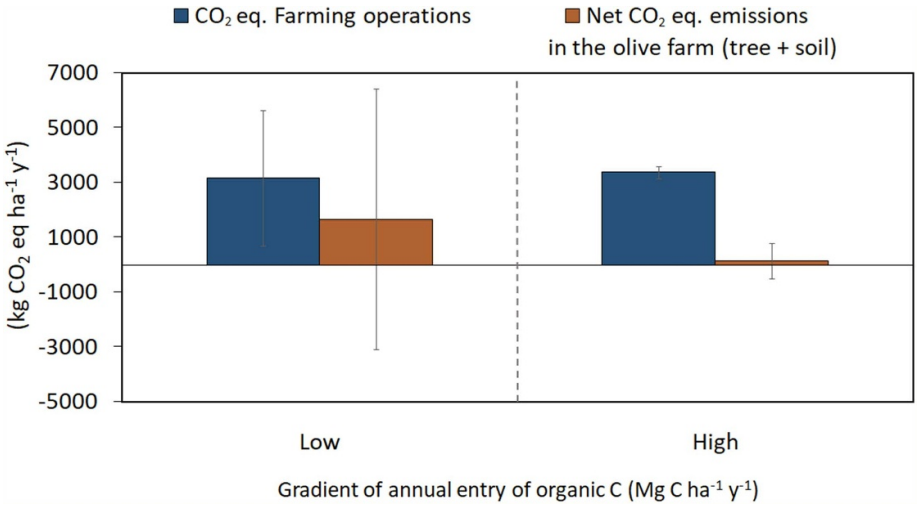

Figure 5. CO_2 eq-emissions (kg CO_2−eq ha^{-1} yr^{-1}) derived from farming operations and net CO_2 eq emissions after subtracting the CO_2 sequestered as organic carbon in the whole farm (soil + tree) in low and high olive groves. Vertical bars represent the standard deviation.

There was a significant linear relationship between manageable annual C-input and annual soil carbon balance ($r^2 = 0.72$; $p < 0.05$) (figure 4(a)), as well as between manageable annual C-input and SOM ($r^2 = 0.60$; $p < 0.05$) (figure 4(b)). In low-input olive groves, such as L1, the annual carbon balance was negative. In contrast, high olive groves, like H1 and H3, achieved a positive carbon balance, reaching up to 1.04 and 1.05 Mg C ha^{-1} yr^{-1}, respectively (figure 4(a)). high olive groves showed the highest SOM values(figure 4(b)).

3.3. CO_2 emissions derived from farming operations and net CO_2 balance

CO_2-eq emissions from farming operations ranged from 906 to 5,796 kg CO_2-eq ha^{-1} y^{-1}, with similar mean values in low and high farms (figure 5).

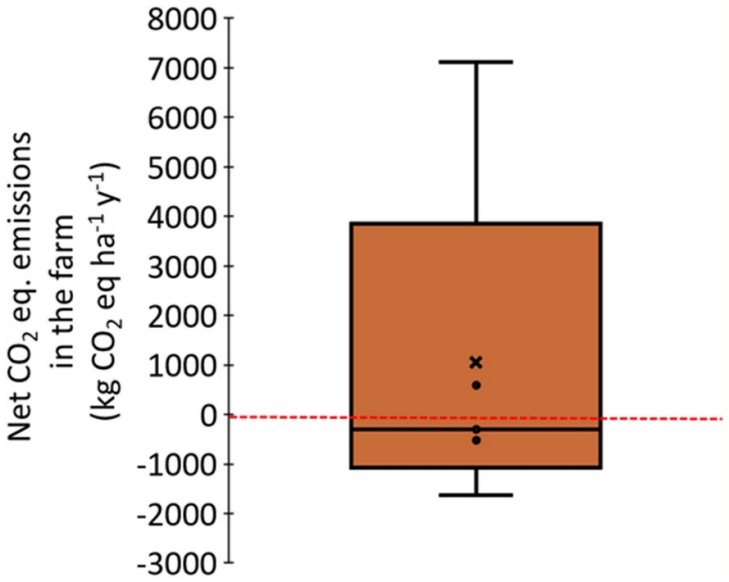

Figure 6. Boxplot of the net CO_2 emissions across the six-olive grove, as kg CO_2 equivalent ha^{-1} yr^{-1}. Boundaries of the boxes closest to, and furthest from zero indicate the 25th and 75th percentiles, respectively. The thin lines within the box mark the median and the *X* mark average. Bars above and below the box indicate the 90th and 10th percentiles, respectively.

To assess the net balance, CO_2 sequestered in the soil and on the farm (negative values) was subtracted from total farm operation CO_2-eq emissions (positive values) (figure 5). When considering the CO_2 sequestered in the farm (tree + soil) organic carbon, the net CO_2 balance remained positive, with numerically lower, although differences were not statistically significant, values for high olive farms (144 kg CO_2−eq ha^{-1} yr^{-1}) compared to low olive farms (1659 kg CO_2−eq ha^{-1} yr^{-1}), although these differences were not statistically significant.

Across the six farms studied, net CO_2 emissions ranged from high levels of emissions (7117 kg CO_2−eq ha^{-1} yr^{-1}) to net carbon gains (as low as −1627 and −514 kg CO_2−eq ha^{-1} yr^{-1}). This wide range highlights significant variability in the farms' net CO_2 dynamics (figure 6).

4. Discussion

4.1. Biogenic carbon balance along a gradient of annual manageable carbon inputs

The overall positive biogenic carbon balance in the studied olive groves, which vary in tree density and management, including integrated, organic, and organic-biodynamic systems, indicates that olive groves function as agroecosystems that annually remove atmospheric CO_2 into organic carbon on the farm. This aligns well with other studies on olive groves (López-Bellido *et al* 2016, Torrús-Castillo *et al* 2023) and other woody crops. For instance, Cammarata *et al* (2025) reported that orange orchards under sustainable management practices achieved a net carbon accumulation in rate of approximately 0.5 Mg CO_2 ha^{-1} yr^{-1}. This value is consistent with the carbon balance observed in our olive groves, further supporting the role of woody perennial crops in mitigating climate change through atmospheric CO_2 removal.

The positive biogenic organic carbon balance can be explained by an increase in organic carbon in the permanent structures of the trees, in the soil as SOC, or both. As expected, trees act as a sink for atmospheric CO_2. Previous studies conducted in Mediterranean olive groves have reported values ranging from 0.51 to 0.58 Mg C ha^{-1} yr^{-1} (Torrús-Castillo *et al* 2023), while lower values around 0.38 Mg C ha^{-1} yr^{-1} have also been reported (Funes *et al* 2022). Notably, the annual atmospheric CO_2 accumulated as organic carbon in the permanent structure of the tree does not vary significantly between groups of olive farms differing in annual organic carbon inputs. This lack of statistical significance may be explained by the high variability observed within the groups, particularly among High-input farms, reflecting heterogeneous management practices under real field conditions. This suggests that management practices leading to an increase in the annual organic carbon input to the soil do not significantly affect the annual growth rate of the trees. This finding supports the conclusion of Torrús-Castillo *et al* (2023), who observed similar annual rates of atmospheric CO_2 sequestration into tree

organic carbon, regardless of the management practices that led to different levels of organic carbon inputs.

The carbon stored annually in the permanent structures of the trees reflects the role of olive groves as agroecosystems that capture atmospheric CO_2 and store it as organic carbon. Assuming the average values for the 400 000 ha of olive groves in Portugal, this would amount to approximately 0.58 Mt of CO_2 annually, representing more than 1% of the 42 Mt of CO_2 that the EU plans to eliminate through carbon farming by 2030 (COM/800, 2021). This carbon sequestration potential highlights the importance of olive groves not only as a source of agricultural production but also as a key ally in the fight against climate change.

According to the additionality criteria established by EU regulations (Regulation (EU) 2024/3012 2024/3012) for quantifying potentially monetizable CO_2 credits through the voluntary market, the annual rate of CO_2 accumulated in olive trees should not be considered if carbon farming practices do not affect this rate during the implementation of the carbon farming project. However, the organic carbon accumulated in trees can remain stored for over a hundred years, at least in traditional olive groves worldwide, similarly to some technologies designed for carbon sequestration. Additionally, the annual rate of arboreal biomass accumulation in the studied olive groves ranged between 710 and 1,000 kg ha^{-1} yr^{-1} (data not shown). Assuming that the calorific value of olive tree dry biomass is approximately 4378 kcal kg^{-1} (de Andalucía 2010), this annual biomass production would correspond to an energy content equivalent to the combustion of 310–438L of diesel, which would otherwise emit 0.77–1.09 t CO_2 ha^{-1} yr^{-1}. Therefore, the permanent structures of olive groves currently play a significant role in mitigating greenhouse gas emissions, which, when extrapolated to the olive-growing area of Portugal, represents a potential mitigation of 310 000–438 000 t CO_2 per year. At current voluntary carbon market prices, this mitigation potential would correspond to an economic value of approximately 23.2 M€ per year, highlighting the significant climate mitigation role of the permanent structures of olive groves. In general, the soil of the studied farms acts as a sink for atmospheric CO_2. However, the biogenic carbon balance in the soil varies depending on the annual inputs of organic carbon received. Low-input systems were associated with negative soil carbon balances, reflecting a net loss of organic carbon. This pattern can be explained by limited organic carbon inputs, particularly due to reduced vegetation cover and the absence of external organic amendments such as manure. Consequently, carbon inputs to the soil failed to offset carbon losses, primarily due to CO_2 emissions and erosion, resulting in a negative biogenic carbon balance. In contrast, higher-input systems promoted positive soil carbon balances. In these cases, the combination of spontaneous vegetation cover with the incorporation of pruning residues and, in some farms (L2 and H3), the application of manure, effectively counterbalanced carbon losses and promoted SOC accumulation. A notable example is L3, where the whole area of the farm was covered by spontaneous cover crops, which resulted in the highest positive biogenic carbon balance, demonstrating the critical role of spontaneous vegetation cover in carbon retention (Pareja-Sánchez *et al* 2024). Indeed, both manure and vegetation cover have been identified as effective strategies for enhancing soil carbon sequestration capacity (Nieto *et al* 2010).

Moreover, this study revealed that SOC content, although influenced by pedoclimatic conditions such as soil texture and clay content (Richardson *et al* 2023), showed a significant positive linear relationship with the annual manageable C-inputs. The observed trend suggests that farms with greater annual C-inputs tend to have higher SOC contents, especially when these practices are consistently applied over time. Thus, although SOC should not be directly interpreted as a proxy for carbon balance due to its multifactorial nature, it can serve as an effective indicator of the degree of implementation of sustainable management practices that promote net atmospheric CO_2 removal in olive groves. Differences in SOC levels were observed not only between management systems but also within them, highlighting the variability associated with management intensity. These differences emphasize that certification schemes alone do not guarantee higher SOC levels, rather, the intensity, continuity, and effectiveness of the management practices are the main drivers.

The strong relationship observed between annual manageable carbon inputs and soil carbon balance is consistent with previous studies identifying carbon inputs as the primary driver of SOC rather than management system type per se (Chenu *et al* 2019). While this mechanism is well established, the novelty of the present study lies in its integrated, farm-scale carbon balance approach, combining tree biomass, soil carbon dynamics, erosion losses, and emissions from agricultural operations under real field conditions.

However, not all studies report such a clear relationship between carbon inputs and soil carbon dynamics. SOC responses to management practices can be highly variable and context-dependent, influenced by factors such as soil type, climate conditions, and management history (Chenu *et al* 2019). In some cases, increases in organic inputs may not immediately result in measurable SOC gains due to

rapid mineralization or equilibrium effects. These discrepancies highlight the importance of site-specific conditions and long-term assessments.

The positive relationship between increased carbon inputs and carbon sequestration can be explained by several interacting mechanisms. The addition of organic matter improves soil structure by promoting aggregate formation, which protects organic carbon from rapid mineralization and enhances its stabilization in the soil. Improved soil structure also increases water infiltration and retention, reducing surface runoff, limiting soil crust formation, and decreasing erosion, which are major pathways of carbon loss in Mediterranean environments. In addition, higher organic matter availability stimulates microbial activity and nutrient cycling, which can indirectly enhance plant productivity and increase biomass inputs to the soil.

Furthermore, the presence of vegetation cover contributes to reducing soil crust formation and improving soil physical properties, reinforcing these processes. While other soil management practices such as plastic mulching may also reduce evaporation and erosion by covering the soil surface, they do not contribute additional carbon inputs and therefore cannot promote long-term carbon sequestration to the same extent as organic matter additions. These results highlight that both the quantity and quality of organic inputs are critical drivers of soil carbon accumulation.

In the analyzed olive groves, most of the annual organic carbon inputs to the soil originated from internal sources, namely carbon produced within the farm itself, such as olive leaf litter, residues from spontaneous vegetation cover and pruning residues, whereas external inputs such as manure and other soil amendments were comparatively limited. This reliance on internal organic inputs means that farmers can implement carbon farming strategies largely independent of external resources. These findings align with those of Almagro *et al* (2016), who highlighted those sustainable practices, including the use of vegetation cover and the incorporation of crop residues, not only enhance SOC accumulation but also contribute to greenhouse gas mitigation. Given these results, many olive groves with a negative soil carbon balance could reverse this trend simply by increasing the incorporation of carbon generated within the farm. Specifically, the widespread implementation of vegetation cover and the application of pruning residues represent viable strategies within carbon farming, particularly in systems with limited access to manure.

Finally, the observed relationship between annual SOC balance and the annual SOC accumulation rate driven by specific management-related carbon inputs provides a quantitative basis for evaluating the effectiveness of these practices within carbon farming and certification frameworks. According to this study, approximately 1.2 Mg C ha^{-1} yr^{-1} would be required to achieve a neutral soil carbon balance, a target that can be feasibly attained through a combination of spontaneous vegetation cover and pruning residues generated within the olive groves themselves.

4.2. CO_2 emissions from agricultural operations and net CO_2 emissions

CO_2 emissions related to agronomic operations in olive groves represent a significant source of greenhouse gases, mainly due to machinery use, fertilization, and tillage practices. Emissions from field operations were relatively consistent across carbon input gradients, suggesting that intensive agricultural practices have a similar impact on emissions regardless of soil carbon inputs. However, the lack of significant statistical variability may indicate an opportunity to implement alternative agronomic practices designed in accordance with carbon gradients and soil conditions, which could reduce emissions and optimize the carbon balance of the overall system. The adoption of low-emission machinery and optimized fertilization schemes could help reduce emissions by up to 20% by 2050 without affecting crop productivity (Aminetzah *et al* 2020).

At the farm level (tree + soil), olive groves with low annual organic carbon inputs tended to act as a net CO_2 source. Despite the biogenic whole farm C balance being positive (the farms are gaining organic carbon), mainly because the annual organic carbon sequestration in the permanent structure of the tree compensates for the annual negative biogenic soil C balance, this sequestration was not sufficient to offset CO_2 emissions derived from farming operations, resulting in a net release of CO_2 to the atmosphere. In contrast, olive groves with higher organic carbon inputs tended to approach carbon neutrality or even act as slight atmospheric CO_2 sinks. Therefore, practices such as incorporating pruning residues along with maintaining spontaneous cover crops, instead of rapidly mineralizing fertilizers, are likely to mitigate CO_2 emissions by stabilizing organic carbon in the soils and reducing the rapid decomposition of organic matter (Álvarez-Solís *et al* 2010).

These management practices, which resulted in an annual organic carbon input exceeding 3 Mg C ha^{-1} yr^{-1}, not only improved the carbon balance and offset the CO_2 eq emissions from farming operations, but also enhanced the long-term sustainability of olive production. This process is framed within a growing interest in carbon markets and sustainable agricultural policies within the EU. Olive

groves, acting as carbon sinks, contribute significantly to CO_2 capture both in soils and in the permanent structure of the trees. This capacity could open new opportunities for farmers to participate in carbon offset schemes, generating carbon credits that provide an additional economic incentive for adopting more sustainable agricultural practices (Torrús-Castillo *et al* 2023). These benefits not only enhance the resilience of olive groves to climate change but also position them as a key tool within the agricultural circular economy. Through practices that reduce emissions and increase carbon capture, farmers can become key players in global efforts to achieve carbon neutrality targets by 2050 (European Commission 2023).

Nevertheless, the carbon sink function of olive groves should be interpreted as temporally limited, as soil and biomass carbon accumulation rates decline as systems approach equilibrium. Carbon sequestration therefore only occurs until a new steady state is reached, meaning that emission offsets cannot be maintained indefinitely. Long-term climate mitigation consequently requires combining carbon input strategies with effective greenhouse gas emission reductions (Chenu *et al* 2019).

4.3. Implications, limitations and policy relevance

These findings have important implications for Mediterranean agriculture and climate policy. In semi-arid regions such as Alentejo, where soils are typically low in organic carbon and highly vulnerable to degradation, increasing annual carbon inputs through sustainable management practices represents a key strategy to enhance soil resilience and mitigate climate change. Practices such as maintaining spontaneous cover crops and incorporating pruning residues can play a central role in improving soil carbon balance while reducing net CO_2 emissions at the farm level.

From a policy perspective, these results support the implementation of carbon farming initiatives promoted by the European Union, including those under the green deal and emerging carbon certification frameworks. Importantly, our findings suggest that increasing carbon inputs is more effective than relying solely on management system labels (e.g. organic or biodynamic) to improve carbon balance. This highlights the need for policy frameworks that prioritize measurable outcomes, such as increases in soil carbon inputs, rather than prescriptive management categories. Furthermore, the variability observed among farms indicates that site-specific approaches and flexible policy instruments may be necessary to maximize the effectiveness of carbon sequestration strategies across Mediterranean agricultural systems.

These results are also relevant in the context of voluntary carbon markets. Olive groves that achieve positive carbon balances or approach carbon neutrality may offer opportunities for farmers to participate in carbon credit schemes, generating additional economic incentives for adopting sustainable practices, as demonstrated in recent assessments of carbon farming projects in Mediterranean olive groves, which quantified both carbon credit generation and associated economic returns (Domouso *et al* 2026). However, the temporal limitations of carbon sequestration, particularly in soils approaching equilibrium, must be carefully considered when designing carbon credit methodologies, as long-term permanence and additionality remain key challenges.

Despite these promising results, several limitations of this study should be acknowledged. First, the relatively small sample size (six olive groves) may limit the generalizability of the findings. Second, the study is region-specific, focusing on olive groves in Alentejo, and therefore results may not be directly transferable to other Mediterranean regions with different soil and climatic conditions. Third, uncertainties associated with carbon accounting approaches, including model-based estimations of soil CO_2 emissions and assumptions related to carbon inputs, may introduce variability in the results.

Finally, these findings highlight the importance of practical, farm-level strategies for improving carbon balance in olive groves. Increasing internal carbon inputs, particularly through vegetation cover and residue management, represents a feasible and scalable approach for farmers. Future research should focus on long-term assessments of carbon dynamics across a wider range of Mediterranean agroecosystems, as well as on improving the accuracy and robustness of carbon accounting methods to support climate policy and carbon market development.

5. Conclusion

Our study demonstrates that agronomic management practices significantly influence the carbon balance in olive groves, affecting both CO_2 emissions and carbon storage in the soils and tree biomass. In 5 out of the 6 olive groves analyzed, carbon balances were positive, highlighting the potential role of this crop in mitigating climate change by capturing atmospheric CO_2 and storing it as organic carbon in the soils and the permanent structures of trees. This process not only delivers environmental functions but also

represents potential economic advantages for farmers who can turn these functions into services and benefits for society.

Although emissions from agricultural operations, such as the use of machinery and chemical fertilizers, are inevitable in more intensive systems, their impact can be largely offset by enhanced carbon inputs from tree biomass growth and the implementation of agronomic practices that enhance SOC. Higher carbon inputs to the soil are directly associated with a trend of reduced net CO_2 emissions, with significant reductions of up to 50% observed in gradients above 3 Mg C ha^{-1} yr^{-1}. This indicates that, beyond certain thresholds of *C* storage, olive groves can become net carbon sinks, especially when slow-degrading materials are introduced to stabilize soil carbon. Regarding net CO_2 balances, olive groves with high gradients (>3.5 Mg C ha^{-1} yr^{-1}) delivered the most effective contributions, reinforcing the value of strategies such as the incorporation into the soils of pruning residues and spontaneous vegetation cover. On the other hand, although intensive systems result in higher emissions rates due to increased agricultural inputs, these emissions can be partially offset by higher productivity rates and increased carbon stored in the system.

Finally, the adoption of sustainable agricultural practices not only improves the carbon balance in olive groves but also potentially results in economic opportunities opening related to carbon markets and emission offsetting programs. Olive groves, acting as carbon sinks, may potentially provide additional incentives for farmers to adopt agronomic strategies that are more tightly aligned with long-term sustainability societal targets and policy goals.

Future research should focus on evaluating the long-term potential of olive groves to achieve carbon neutrality under different management scenarios. Particular attention should be given to the role of soil management practices in sustaining carbon sequestration over time. In addition, further studies across a wider range of Mediterranean regions are needed to better capture variability in soil and climatic conditions and to improve the robustness of carbon accounting approaches.

Acknowledgments

Authors from the University of Évora would like to acknowledge funding from the Portuguese Foundation for Science and Technology for funding their research through Projects UIDB/05183/2020 (Mediterranean Institute for Agriculture, Environment and Development—MED https://doi.org/10.54499/UIDB/05183/2020) and LA/P/0121/2020 (CHANGE Lab for Global Change and Sustainability—https://doi.org/10.54499/LA/P/0121/2020) as well as Project SOLVO (https://doi.org/10.54499/2022.06004.PTDC). Sergio Prats was supported by the Portuguese Science Foundation (FCT) through the research Contract CEECIND/01473/2020 and the Spanish Ministry of Science, Innovation and Universities through the research Contract RYC2022-035489-I. All authors would like to thank the PRIMA Foundation who provided funds for the original research, conducted under the SUSTAINOLIVE project.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflict of interest

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

Author contributions

Evangelina Pareja-Sánchez 0000-0002-2702-100X
Formal analysis (equal), Visualization (equal), Writing – original draft (equal), Writing – review & editing (equal)

Sergio A Prats 0000-0002-7341-877X
Data curation (equal), Formal analysis (equal), Investigation (equal), Writing – review & editing (equal)

Roberto García-Ruíz 0000-0001-9277-1993
Visualization (equal), Writing – review & editing (equal)

Anna I De Luca 0000-0002-8716-8177
Data curation (equal), Investigation (equal), Writing – review & editing (equal)

José Muñoz-Rojas 0000-0001-5331-8344
Conceptualization (equal), Visualization (equal), Writing – review & editing (equal)

References

Almagro M, de Vente J, Boix-Fayos C, García-Franco N, Melgares de Aguilar J, González D, Solé-Benet A and Martínez-Mena M 2016 Sustainable land management practices as providers of several ecosystem services under rainfed Mediterranean agroecosystems *Mitig Adapt. Strateg. Glob. Change* **21** 1029–43

Álvarez-Solís J D, Gómez-Velasco D A, León-Martínez N S and Gutiérrez-Miceli F A 2010 Integrated management of inorganic and organic fertilizers in maize cropping *Agrociencia* **44** 575–86

Alves C A, Vicente E D, Evtyugina M, Vicente A, Pio C, Fernández Amado M and López Mahía P 2019 Gaseous and speciated particulate emissions from the open burning of wastes from tree pruning *Atmos. Res.* **226** 110–21

Aminetzah D, Denis N, Henderson K, Katz J and Mannion P 2020 *Reducing Agriculture Emissions through Improved Farming Practices* (McKinsey & Company)

Anderson J M and Ingram J S I 1993 Tropical soil biology and fertility: a handbook of methods *J. Ecol.* **78** 547

Bäckstrand K 2022 *Towards A Climate-Neutral Union by 2050? the European Green Deal, Climate Law, and Green Recovery in Routes to A Resilient European Union* ed A Bakardjieva Engelbrekt *et al* (Palgrave Macmillan) (https://doi.org/10.1007/978-3-030-93165-0_3)

Cammarata M, Tadiello T, Scuderi A, Millar N and Basso B 2025 Regenerative practices can lead to carbon-negative orange groves in Sicily *J. Agric. Food Res.* **19** 101615

Castro J, Fernández-Ondoño E, Rodríguez C, Lallena A M, Sierra M and Aguilar J 2008 Effects of different olive-grove management systems on the organic carbon and nitrogen content of the soil in Jaén (Spain) *Soil Tillage Res.* **98** 56–67

Chenu C, Angers D A, Barré P, Derrien D, Arrouays D and Balesdent J 2019 Increasing organic carbon stocks in agricultural soils: knowledge gaps and potential innovations *Soil Tillage Res.* **188** 41–52

Coleman K and Jenkinson D S 1996 *RothC-26.3—a Model for the Turnover of Carbon in Soil in Evaluation of Soil Organic Matter Models ed* D S Powlson, P Smith and J U Smith (Springer) pp 237–46

COM/2021/800 2021 *Communication from the Commission to the European Parliament and the Council: Sustainable Carbon Cycles* (European Commission)

de Andalucía J, 2010. Potencial energético de los subproductos de la industria olivarera en Andalucía (available at: www.juntadeandalucia.es/export/drupaljda/Potencial%20energ%C3%A9tico.pdf) (Accessed 31 March 2025)

de Graaff J Duarte F Fleskens L and de Figueiredo T 2010 The future of olive groves on sloping land and ex-ante assessment of cross compliance for erosion control *Land Use Policy* **27** 33–41

De Luca A I, Iofrida N, de Molina González M, Spada E, Domouso P, Falcone G, Gulisano G and García-Ruiz R 2023 A methodological proposal of the Sustainolive international research project to drive Mediterranean olive ecosystems toward sustainability *Front. Sustain. Food Syst.* **7** 1207972

Desideri U, Arcioni L, Leonardi D, Cesaretti L, Perugini P, Agabitini E and Evangelisti N 2014 Design of a multipurpose 'zero energy consumption' building according to European Directive 2010/31/EU: life cycle assessment *Energy Build.* **80** 585–97

Domouso P, Pareja-Sánchez E, Lechuga-Punal J, García-Moreno A J, Ochoa-Esteban V and García-Ruiz R 2026 Carbon farming in Mediterranean olive groves: potential for carbon credits and policy implications *J. Environ. Manage.* **398** 128464

Don A, Poeplau C, Freibauer A and Zanchi G 2023 Carbon sequestration in soils and climate change mitigation: definitions and pitfalls *Glob. Change Biol.* **29** 351–65

European Commission—JRC 2011 Recommendations for life cycle impact assessment in the European context—ILCD handbook European Commission—JRC 2012 technical notes for characterization factors of the ILCD recommended life cycle impact assessment methods

European Commission 2017 PEFCR guidance document—guidance for the development of product environmental footprint category rules (PEFCRs), version 6.3

European Commission 2021 List of potential agricultural practices that eco-schemes could support (available at: https://agriculture.ec.europa.eu/news/commission-publishes-list-potential-eco-schemes-2021-01-14_en)

European Commission 2023 EU 2050 Targets (available at: https://commission.europa.eu)

FAO, ITPS 2018 Global soil organic carbon map (GSOCmap): technical report (FAO)

Fernández-Lobato L, García-Ruiz R, Jurado F and Vera D 2021 Life cycle assessment, carbon footprint and carbon balance of virgin olive oil production *J. Environ. Manage.* **293** 112951

Funes I, Molowny-Horas R, Savé R, De Herralde F, Aranda X and Vayreda J 2022 Carbon stocks and changes in biomass of Mediterranean woody crops *Agron. Sustain. Dev.* **42** 98

García-Ruiz R, Ochoa M I, Hinojosa M B and Gómez-Muñoz B 2012 Improved soil quality after 16 years of olive mill pomace application *Agron. Sustain. Dev.* **32** 803–10

Gómez J A, Campos M, Guzmán G, Castillo-Llanque F, Vanwalleghem T, Lora Á and Giráldez J V 2018 Soil erosion control, plant diversity and arthropod communities under heterogeneous cover crops *Environ. Sci. Pollut. Res.* **25** 977–89

Gómez J A, Reyna-Bowen L, Rebollo P F and Soriano M A 2022 Comparison of soil organic carbon stocks evolution in two olive orchards with different planting systems in southern Spain *Agriculture* **12** 432

Gómez-Muñoz B, Hatch D J, Bol R and García-Ruiz R 2014 Nutrient dynamics during decomposition of plant cover residues Agric *Ecosyst. Environ.* **184** 115–23

Griscom B W *et al* 2017 Natural climate solutions *Proc. Natl Acad. Sci. USA* **114** 11645–50

INE 2024 Agricultural Statistics 2021 (Lisbon: instituto Nacional de Estatística) (available at: www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_destaques&DESTAQUESdest_boui=539491784&DESTAQUESmodo=2) Accessed 23 October 2024

IPCC 2006 2006 IPCC Guidelines for National Greenhouse Gas Inventories *Agriculture, Forestry and Other Land Use* (*Generic Methodologies Applicable to Multiple Land-Use Categories* vol 4) (Intergovernmental Panel on Climate Change)

IPMA 2024 Instituto Português do Mar e da Atmosfera (available at: www.ipma.pt/bin/file.data/climate-normal/cn_81-10_EVORA.pdf)

Lal R 2004 Soil carbon sequestration impacts on global climate change and food security *Science* **304** 1623–7

López-Bellido P J, López-Bellido L, Fernández-García P, Muñoz-Romero V and López-Bellido F J 2016 Assessment of carbon sequestration in olive groves *Carbon Manage.* **7** 161–70

Ma S, He F, Tian D, Zou D, Yan Z, Yang Y, Zhou T, Huang K, Shen H and Fang J 2018 Variations and determinants of carbon content in plants: a global synthesis *Biogeosciences* **15** 693–702

Metzidakis I, Martinez-Vilela A, Nieto G C and Basso B 2008 Intensive olive orchards on sloping land: good water and pest management are essential *J. Environ. Manage.* **89** 120–8

Muñoz-Rojas J, Guiomar N, Pinto-Correia T and Prats S 2024 Pedoclimatic and landscape conditions of olive groves in Portugal and Alentejo *The Olive Landscapes of the Mediterranean* (*Landscape Series* vol 36) ed J Muñoz-Rojas and R García-Ruiz (Springer)

Nelson D W and Sommers L E 1996 *Total Carbon, Organic Carbon, and Organic Matter in Methods of Soil Analysis. Part 3—Chemical Methods* (Soil Science Society of America) pp 961–1010

Nieto O M, Castro J, Fernández E and Smith P 2010 Simulation of soil organic carbon stocks in a Mediterranean olive grove under different soil-management systems using the RothC model *Soil Use Manage.* **26** 118–25

Pareja-Sánchez E, Calero J and García-Ruiz R 2024 Does spontaneous cover crop increase the stocks of soil organic carbon and nitrogen in commercial olive orchard? *Soil Tillage Res.* **244** 106237

Pareja-Sánchez E, Cantero-Martínez C, Álvaro-Fuentes J and Plaza-Bonilla D 2020 Soil organic carbon sequestration when converting a rainfed cropping system to irrigated corn under different tillage systems and N fertilizer rates *Soil Sci. Soc. Am. J.* **84** 1219–32

Plaza-Bonilla D, Arrúe J L, Cantero-Martínez C, Fanlo R, Iglesias A and Álvaro-Fuentes J 2015 Carbon management in dryland agricultural systems: a review *Agron. Sustain. Dev.* **35** 1319–34

Prats S A, Malvar M C, Vieira D C S, MacDonald L and Keizer J J 2016 Effectiveness of hydromulching to reduce runoff and erosion in a recently burnt pine plantation in central Portugal *Land Degrad. Dev.* **27** 1319–33

Proietti S, Sdringola P, Desideri U, Zepparelli F, Brunori A, Ilarioni L, Nasini L, Regni L and Proietti P 2014 Carbon footprint of an olive tree grove *Appl. Energy* **127** 115–24

Regulation (EU) 2024/3012 2024 Regulation of the European parliament and of the council on the certification of carbon removals in the EU Official Journal of the European Union (available at: www.boe.es/buscar/doc.php?id=DOUE-L-2024-81804)

Richardson G S, Ruark M D, Radatz T, Radatz A, Cooley E, Silva E M, Augarten A J, Zhu J and Zegler C H 2023 The influence of inherent soil factors and agricultural management on soil organic matter *Ecosphere* **14** e4459

Rodríguez Sousa A A, Muñoz-Rojas J, Brígido C and Prats S A 2023 Impacts of agricultural intensification on soil erosion and sustainability of olive groves in Alentejo (Portugal) *Landsc. Ecol.* **38** 3479–98

Rodríguez Sousa A A, Muñoz-Rojas J, Pinto-Correia T, Aguilera P A, Barandica J M and Rescia A J 2021 A comparative analysis of soil loss tolerance and productivity of olive groves in PDO areas *Agronomy* **11** 665

Ruiz-Carrasco B, Pareja-Sánchez E, Liétor J, Vera D, Fernández-Lobato L and García-Ruiz R 2026 Field-based assessment of carbon farming practices in Mediterranean olive groves: emission reductions and sequestration outcomes *J. Clean. Prod.* **543** 147562

Salomone R, Cappelletti G M, Malandrino O, Mistretta M, Neri E, Nicoletti G M, Notarnicola B, Pattara C, Russo C and Saija G 2015 *Life Cycle Assessment in the Olive Oil Sector in Life Cycle Assessment in the Agri-Food Sector* (Springer) (https://doi.org/10.1007/978-3-319-11940-3_2)

Salomone R and Ioppolo G 2012 Environmental impacts of olive oil production: a Life Cycle Assessment case study in the province of Messina (Sicily) *J. Clean. Prod.* **28** 88–100

Sánchez-Monedero M A, Cayuela M L, Mondini C, Serramiá N and Roig A 2008 Potential of olive mill wastes for soil C sequestration *Waste Manage.* **28** 767–73

Smith P *et al* 2008 Greenhouse gas mitigation in agriculture *Phil. Trans. R. Soc. B* **363** 789–813

Torrús-Castillo M, Calero J and García-Ruiz R 2023 Does olive cultivation sequester carbon? Carbon balance along a C input gradient *Agric. Ecosyst. Environ.* **358** 108707

Torrús-Castillo M, Domouso P, Herrera-Rodríguez J M, Calero J and García-Ruiz R 2022 Aboveground carbon fixation and nutrient retention in temporary spontaneous cover crops in olive groves of Andalusia *Front. Environ. Sci.* **10** 868410

Velázquez-Martí B, Cortés I L and Salazar-Hernández D M 2014 Dendrometric analysis of olive trees for wood biomass quantification in Mediterranean orchards *Agrofor. Syst.* **88** 755–65