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ORIGINAL PAPER

Climatic and economic benefits of agriculture-based mitigation in Mediterranean tree crop ecosystems

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Abstract

Mediterranean tree crops provide land-based mitigation services by storing carbon long-term in soil and wood. However, their mitigation potential has often been overlooked due to the lack of robust, context-specific estimates. This limits the development of targeted policies to support farmers involved in "carbon farming"—the use of agricultural practices to enhance CO_2 absorption. This study presents a model-based carbon accounting framework for assessing the climatic and economic benefits of agriculture-based mitigation in Mediterranean tree crop ecosystems. The approach does not rely on extensive field monitoring as its primary data source; however, it is calibrated and validated against targeted field measurements and experimental datasets generated within the LIFE CLIMATREE project, which constitute the validation basis of the analysis. The framework quantifies carbon removals and emissions under three management scenarios, ranging from business-as-usual practices to mitigation-rich management. Across representative Mediterranean countries and tree crops, mitigation-rich practices result in additional removals of approximately 1–2.5 t CO_2 ha^{-1} yr^{-1}, with considerable variation across crop types and regions. These additional removals translate into meaningful economic values when assessed using indicative carbon prices, highlighting the potential contribution of tree crop management to climate action and agricultural sustainability. The findings support the development of carbon markets, eco-labeling, and agri-environmental schemes under the new Common Agricultural Policy. They also contribute to improving the accuracy of national GHG inventories in the LULUCF sector, which currently do not differentiate between orchard species or management practices. This evidence base is essential for shaping more effective climate policies and incentivizing sustainable land use.

Keywords Land-based mitigation · Carbon farming · Common Agricultural Policy · Carbon sequestration · Climate Action (SDG13)

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Introduction

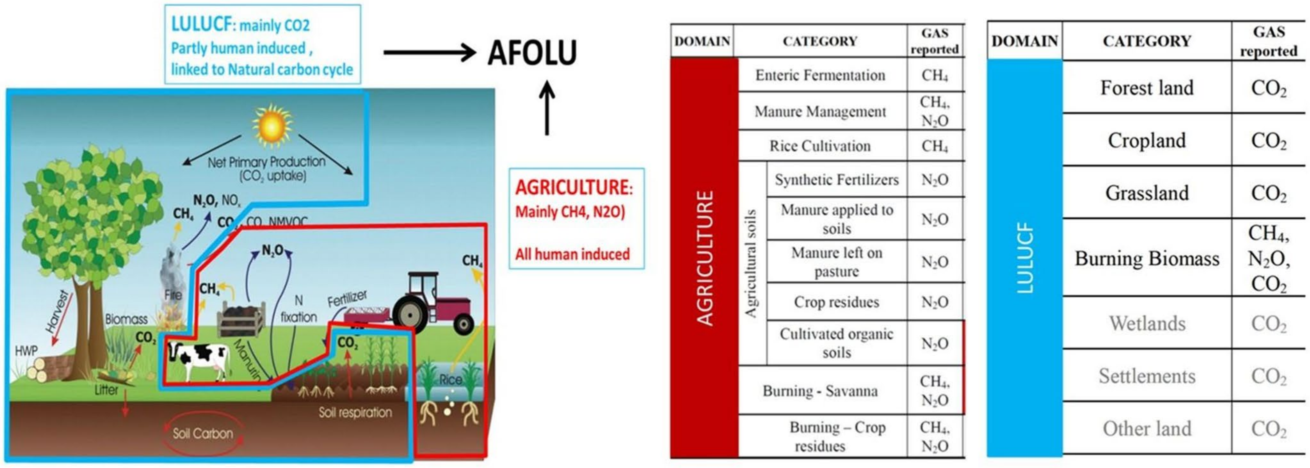
Land-based ecosystems such as orchards, forests and agricultural land are key contributors to the sequestration of atmospheric CO_2. Activities within the Agriculture, Forestry and other Land Use (AFOLU) sector were responsible for approximately 13% of CO_2, 44% of CH_4, and 82% of N_2O emissions attributable to human activities from 2007 to 2016. Overall, this corresponds to around 23% (12.0 ± 3.0 Gt CO_2 eq yr^{-1}) of total anthropogenic greenhouse gas (GHG) emissions worldwide (IPCC 2023). As part of the AFOLU sector, cultivation activities act as both sources and sinks for GHG, highlighting their dual contribution to global warming and mitigation. Sustainable agricultural ecosystems, which occupy nearly 40% of the Earth's terrestrial surface (Smith 2012; IPCC 2022), can sequester substantial carbon in biomass, litter, and soil pools (Nair et al. 2009). Several agricultural management practices, such as no-tillage, cover cropping, use of organic fertilizers, and mulching of pruning residues, enhance sequestration while reducing emissions, thus forming mitigation-rich practices (Bithas and Latinopoulos 2021; Fiore et al. 2015; Montanaro et al. 2017). Given the extensive cropland in Mediterranean regions, these practices could be decisive in achieving low-carbon agricultural transitions.

Tree crops, and orchards in particular, may play an important role due to their perennial character, which enables long-term carbon storage in both soils and woody biomass (Filipovic et al. 2025). Empirical evidence further suggests that perennial agricultural and agroforestry systems tend to achieve higher levels of carbon sequestration compared to other types of farming systems, reaching rates similar to or greater than those observed in forests (Hammad et al. 2020; Montagnini and Nair 2004; Nair et al. 2010; Schoeneberger 2009; Proietti et al. 2016; Toensmeier 2017). However, estimates vary widely due to differences in carbon accounting methodologies and GHG inventory assumptions within the Land Use, Land Use Change and Forestry (LULUCF) sector (Montanaro et al. 2021; Wu et al. 2012; Zanotelli et al. 2015). Reported sequestration rates range from 2.4 to 12.5 t C ha^{-1} yr^{-1} in orchards (Demestihas et al. 2017), approximately 3 t C ha^{-1} yr^{-1} in mature apple orchards (Zanotelli et al. 2018), 6.3–6.5 t C ha^{-1} yr^{-1} in orange orchards (Consoli et al. 2013) and 11.6–13.45 t C ha^{-1} yr^{-1} in Mediterranean olive orchards (Nardino et al. 2013). In Chinese apple orchards, net sequestration from 1990 to 2010 accounted for 4.5% of China's total terrestrial carbon sink (Wu et al. 2012). Beyond their climatic benefits, orchards deliver multiple ecosystem services—including fruit provisioning, soil fertility, water regulation, pest control, and pollination—supporting local economies and sustainable development, especially in Mediterranean countries where tree crops occupy a large share of cultivated land (Asbjornsen et al. 2014; Demestihas et al. 2017, 2019; Pardo et al. 2017).

Yet, despite their potential, tree crops remain underrepresented in GHG inventories (Montanaro et al. 2021; Valentini 2015; Zomer et al. 2016). This is partly related to the current architecture of the GHG accounting frameworks, which split the C fluxes of agriculture-related activities into different sectors and categories. Within the AFOLU sector, the LULUCF domain accounts for emissions and removals by land-use category, considering biological components such as living biomass, deadwood, litter, and soil organic carbon. However, short-lived biogenic elements (e.g., fruit, leaves, twigs) are excluded, while emissions from farm-level practices—such as fertilizer use, residue burning, or livestock management—are reported separately under "Agriculture." Likewise, fuel combustion on farms is classified under the Energy sector. This fragmented accounting structure prevents a comprehensive CO_2 balance for tree crops, limiting the development of effective carbon farming instruments. As a result, the actual CO_2 balance of tree cultivations cannot be evaluated within a scientifically robust framework. This inhibits the design of appropriate instruments to support the realization of relevant mitigation potential (carbon farming) (Toudert et al. 2018; Bellassen et al. 2022). Figure 1 illustrates the schematic of the AFOLU sector.

Furthermore, the absence of financial incentives discourages farmers from adopting carbon farming practices, despite their environmental benefits. Establishing a comprehensive reward system for CO_2 removals is therefore essential to strengthen the contribution of agriculture to a carbon-neutral economy (Rodriguez-Entrena et al. 2012). Developing such mechanisms requires monetizing the positive externality of CO_2 sequestration. However, only a limited number of studies have assessed the economic value of carbon sequestration in agricultural and agroforestry systems (Aertsens et al. 2013; Bithas and Latinopoulos 2021; Sánchez et al. 2016; Rodriguez-Entrena et al. 2012; Glenk and Colombo 2011; Granado-Díaz et al. 2019; Roesch-McNally and Rabotyagov 2016; Burnett et al. 2024).

To address these gaps, this study develops a methodology to evaluate the full carbon balance of tree crops, trying to facilitate the identification of differences in orchard species, climatic and geophysical conditions, as well as agronomic practices. The novelty lies in the functional integration of elements derived from biogenic processes (as reflected in IPCC 2006) with elements of the Life Cycle Assessment capturing the impacts of management practices (ISO 14067). This integration is operationalized through the "CO_2 Removal Capacity Algorithm" (CO_2RCA), a unified and practice-oriented framework tailored to Mediterranean perennial cropping systems. Rather than treating biogenic removals and management-related emissions as parallel or



DOMAIN		CATEGORY	GAS reported
AGRICULTURE		Enteric Fermentation	CH_4
		Manure Management	CH_4, N_2O
		Rice Cultivation	CH_4
	Agricultural soils	Synthetic Fertilizers	N_2O
		Manure applied to soils	N_2O
		Manure left on pasture	N_2O
		Crop residues	N_2O
		Cultivated organic soils	N_2O
		Burning - Savanna	CH_4, N_2O
		Burning – Crop residues	CH_4, N_2O

DOMAIN	CATEGORY	GAS reported
LULUCF	Forest land	CO_2
	Cropland	CO_2
	Grassland	CO_2
	Burning Biomass	CH_4, N_2O, CO_2
	Wetlands	CO_2
	Settlements	CO_2
	Other land	CO_2

Fig. 1 Schematic representation of the various components of the Agriculture, Forestry and Other Land Use (AFOLU) sector and the greenhouse gas associated with the various categories of the Agriculture and LULUCF domain belonging to the AFOLU sector (from IPCC 2006; with modifications)

Table 1 Cultivation statistics of olives, oranges, apples, peaches and almonds in Spain, Italy and Greece for the years 2012 to 2016

		Olive			Orange	
	YD (t ha^{-1})	PD (trees ha^{-1})	S (Ha)	YD (t ha^{-1})	PD (trees ha^{-1})	S (ha)
Spain	2.64	460	2,429,222	23.81	416	137,009
Italy	2.45	156	1,128,634	20.87	240	84,421
Greece	4.19	173	815,073	23.15	446	33,886
		Apple			**Peach**	
	YD (t ha^{-1})	PD (trees ha^{-1})	S (Ha)	YD (t ha^{-1})	PD (trees ha^{-1})	S (ha)
Spain	19.11	495	28,664	26.14	500	44,582
Italy	45.18	1,350	52,362	20.84	650	68,226
Greece	22.62	739	11,168	15.70	439	39,283
		Almond				
	YD (t ha^{-1})	PD (trees ha^{-1})	S (Ha)			
Spain	0.39	238	495,924			
Italy	1.36	270	28,155			
Greece	2.31	279	13,300			

		Apple			Peach	
	YD (t ha^{-1})	PD (trees ha^{-1})	S (Ha)	YD (t ha^{-1})	PD (trees ha^{-1})	S (ha)
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Spain	0.39	238	495,924			
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Greece	2.31	279	13,300			

disconnected assessments—as is common in the existing literature—CO_2RCA links biological carbon processes and agronomic management decisions at a common spatial and analytical scale, enabling consistent comparison of mitigation-rich practices across crops, regions, and scenarios. This allows the analysis to move beyond plot-scale accounting or carbon stock estimates and instead facilitate policy-relevant evaluation of carbon farming practices at a regional scale.

The analysis was performed at the regional (NUTS-3) scale and focuses on five representative Mediterranean tree crops - olive, orange, peach, apple, and almond - in Greece, Italy, and Spain. It quantifies both the net CO_2 balance per management scenario and the additional CO_2 removal potential induced by mitigation-rich practices, together with their economic valuation as an ecosystem service. By revealing spatial variation in mitigation potential and associated economic values, the analysis provides insights relevant for the design of agricultural–climate policies, eco-schemes, and voluntary carbon market incentives, and helps identify priority regions where targeted incentives may accelerate the adoption of carbon farming practices. In this way, the study supports the EU's 2030 climate targets and advances the integration of carbon farming into evidence-based regional planning.

Methods

Conceptual framework

Selection of representative tree crops

This study proposes a novel methodology to estimate the CO_2 balance of orchards and thereby quantify their contribution to climate change mitigation. The initial step involved identifying representative tree crops across Mediterranean countries. Selection was based on three primary criteria: (a) total cultivated area (ha); (b) average lifespan of tree crop (Years); and (c) annual yield levels (Tons per Hectare). Based on these criteria, we identified five dominant tree-crop cultivations in selected countries (Greece, Italy, Spain): olives; oranges; peaches; apples; and almonds.

In 2017, olive groves covered approximately 4.59 million hectares within the EU, with the majority of this area located in Mediterranean regions. Spain accounted for 55% of this area, Italy 23% and Greece 15%. Spain, Italy and Greece are also the EU's largest citrus fruit (oranges, small citrus fruits and lemons) producing countries. Citrus plantations covered 455,000 ha across the EU in 2017, with Spain accounting for 60%, Italy 27% and Greece 9%. Orange groves accounted for just over half (56%) of the citrus fruit plantations in the EU. Peach orchards (including nectarines) covered 190,500 ha in the EU in 2017, with Spain accounting for two-fifths (41%) of the EU total, with Italy and Greece having the next largest peach orchards. Apple orchards in the EU covered 473,500 ha in 2017, of which Spain accounted for 5.8%. Moreover, apple orchards expanded by 23,900 ha between 2012 and 2017, of which 3,600 ha were in Italy. Finally, almond orchards across the EU covered 743,000 ha in 2017 (22.5% of the total EU fruit growing area), of which Spain accounted for the largest area (85.2% of the EU total) (Eurostat 2019).

Table 2 Sources of data and coefficients used in the CO_2RCA algorithm

Cultivation performance (e.g., yield, planting density, cultivated surface)	Official national statistical data for each country covering five consecutive years (2012–2016)
Wood biomass data	Derived from field experiments conducted by the Agricultural University of Athens during the Life project Climatree
Fertilizers and pesticides data	Values from Green (1987), Audsley et al. (2009) and Lal (2004)
Fossil fuels use	Obtained from the Greenhouse Gas Protocol Tool for Mobile Combustion (GHG Emissions Calculation Tool, Version 2.6) developed by the World Resources Institute
Electricity data	Sourced from (a) the European Environment Agency, b) the International Energy Agency, "Global Energy & CO_2 Status Report, The latest trends in energy and emissions in 2018, 2019"
Agricultural practices data	Information collected and analyzed by the Agricultural University of Athens through a questionnaire survey administered to more than 300 Greek farmers during the Life project Climatree.
Climatological data	Monthly averages for temperature, rainfall and open pan evaporation (2008–2012).
Soil characteristics	LUCAS 2009, TOPSOIL dataset (Orgiazzi et al. 2018; Tóth et al. 2013)

Integration of data and methodological elements for CO_2 balance estimation

Using national statistics for 2012 to 2016, the mean values of yield density (YD, t ha^{-1}), planting density (PD, trees ha^{-1}) and cultivated surface (S, ha) are presented in Table 2 for the case countries. The study focused on the development of a methodology which simultaneously accounts for biogenic carbon removals and anthropogenic emissions. This was achieved by integrating IPCC (2006) elements that reflect the biological cycle of trees with Life Cycle Assessment (LCA) principles (ISO 14067) capturing management-related impacts. The objective is to estimate the actual CO_2 balance at the orchard (farm) level. The methodology draws on: (a) international literature (peer-reviewed and grey literature, including reports); (b) expert interviews; and (c) field experiments and measurements.

Based on this integration, the CO_2 Removal Capacity Algorithm (CO_2RCA) was developed to calculate the annual CO_2 balance of tree crops. A key innovation of this Algorithm is that it provides crop-specific results for different permanent tree crops. To date, the official reporting of CO_2 (National Inventory Reports) makes no distinction between different types of permanent crops or their specific management practices. The resulted outputs were subsequently integrated into a GIS environment in order to estimate the aggregate mitigation potential of tree cultivations at the regional level (NUTS3 level). After estimating mitigation potential, we assigned a monetary value to these removals.

IPCC and LCA methodology

IPCC-based methodological elements

Guidelines were provided by the Intergovernmental Panel on Climate Change (IPCC 2015) for estimating and reporting greenhouse gas emissions and removals. The Land Use, Land-Use Change and Forestry (LULUCF) sector includes orchards within its cropland component. The IPCC-based framework examines the CO_2 pools induced by the ecological-biological function of trees (the biological cycle of orchards), and how human activities influence these pools. Tree biology is linked with three key carbon pools: biomass, soil carbon, and dead organic matter (litter). GHG Inventories classify carbon pool estimation methods in three tiers—Tier 1, Tier 2, and Tier 3—reflecting progressively higher levels of precision (i.e. increased data requirements) and methodological sophistication. As the IPCC-based methodology is designed for aggregating CO_2 reporting objectives, it is not suitable for evaluating different cultivation-management practices based on their effect on CO_2 balance (Montanaro et al. 2017).

LCA-based methodological elements

Hence, the IPCC-based methodology cannot facilitate the assessment of cultivation practices at the individual farm level. For this reason, the methodology proposed in the present study incorporates Life Cycle Assessment (LCA), enabling the evaluation of the actual environmental impact of agricultural management practices at farm level (Pergola et al. 2017). When conducting an LCA analysis, the complete crop lifespan cycle of orchards is considered, encompassing all stages from planting the trees to the disposal of the crop system at the end of its cycle.

While adopting crucial elements of the LCA, this study does not comply with all LCA standards in full. The analysis can be viewed as a Life Cycle Assessment (LCA)-based framework, which is centered around three primary pillars: the utilization of natural resources (such as water and soil); the application of materials and substances (including irrigation systems, compost, pesticides, fertilizers, etc.); and the use of agricultural machinery (such as tractors and plows) for cultivation activities (Aguilera et al. 2015). System boundaries were established at the farm gate, encompassing all the processes related to material and energy inputs and outputs for the selected system. This also includes processes associated with the complete removal of the orchard at the end of its life cycle.

Estimating the carbon balance at the farm level

Development and input parameters of the CO_2 removal capacity algorithm (CO_2RCA)

Merging the necessary elements of two relevant methodologies (i.e., the biogenic carbon removal process, adopted by IPCC 17 and the LCA), an algorithm – referred to as CO_2RCA (CO_2 Removal Capacity Algorithm) – was developed. It calculates the annual CO_2 balance of the selected tree crops in three Mediterranean countries, systematically accounting for CO_2 removals and emissions. The Algorithm estimates biomass and soil components by accounting for the balance between two processes: (1) the CO_2 removed from the atmosphere associated with the formation of new woody biomass, including below-ground biomass; and (2) the CO_2 emitted to atmosphere due to the applied cultivation practices. Greenhouse gas emissions were expressed as CO_2-equivalent mass and are calculated for each input material and energy source required for orchard establishment, management, protection, and harvesting activities.

To this end, the CO_2RCA algorithm incorporated the following factors: (i) Orchard tree planting density, (ii) crop yield, (iii) total orchard surface area, (iv) the development phase of the trees, (v) Amount of pruning residues and associated management operations (tillage, trimming, spraying, irrigation), (vi) Annual amount and specific categories of fertilizers and agrochemicals applied, (vii) Annual energy consumption in terms of fossil fuels and electricity, as well as (viii) Soil characteristics (clay content on topsoil) and climatic conditions (monthly rainfall, open pan evaporation, and average air temperature), based on the geographical location of each cultivated plot.

CO_2RCA can assess the feasibility of implementing various alternative cultivation practices, helping to prioritize those with the highest mitigation potential. Mitigation rich agricultural practices which are evaluated by the CO_2RCA algorithm (Aguilera et al. 2015; Spanos et al. 2021; Vicente-Vicente et al. 2016), are the following:

- Implementation of cover crops, including the use of leguminous species,
- Application of mulching practices,
- Application of fertilizers through fertigation systems,
- Application of insect monitoring techniques and/or mass trapping methods,
- Utilization of pruning residues as solid fuel, substituting diesel consumption,
- Integration of renewable energy sources.

Structure and functional components of the CO_2RCA algorithm

To support the calculation of the CO₂ balance for various tree crops under different cultivation scenarios, an electronic tool was developed based on the CO₂ Removal Capacity Algorithm (CO₂RCA). This tool (available here) translates the algorithm into an accessible, structured format, allowing users to estimate carbon removals and emissions associated with cultivation practices. It is organized into four main components—CO₂ Removal, CO₂ Storage, CO₂ Emissions, and CO₂ Gain—each corresponding to a distinct aspect of the carbon balance. These are described in detail below.

i *CO_2Removal*: This section calculates the amount of CO_2 removed from the atmosphere through the formation of new biomass. This removal reflects changes associated with the production of fruits and the development of trunk, branches, and roots.
ii *CO_2 Storage*: Here, the algorithm determines the amount of CO_2 stored in the soil beneath and around the trees. The dynamics of carbon in soil are based on the RothC model (Coleman and Jenkinson 1996; Coleman et al. 1997), and the algorithm uses monthly steps to calculate the organic soil carbon. The incoming carbon in our case is fruit from thinning processes, leaves, and the pruning residue left on the field, while the Soil Organic Carbon (SOC) is modeled on four active connected pools and an inner organic matter pool (IOM). Each pool decomposes according to first-order process at a characteristic rate.
iii *CO_2 Emissions*: Through LCA, this section measures the CO_2 emissions released into the atmosphere resulting from the current cultivation practices being employed.
iv *CO_2 Gain*: The contribution of cultivation practices (carbon farming) to CO_2 emission reduction.

By incorporating these four sections, the CO_2RCA algorithm provides a comprehensive analysis of CO_2 fluxes, including removal, storage, emissions, and potential gains resulting from different cultivation practices. In this framework, the Annual CO_2 Removal Capacity (ARC) is defined as follows (all variables in this equation are expressed in t CO₂ yr⁻¹):

$$ARC = ARB + ASS - TAE + TAG \tag{1}$$

where *ARB* is the annual CO_2 removal resulting from the changes in tree biomass, *ASS* is the annual CO_2 storage in soil, *TAE* represents the CO_2 total annual emissions and *TAG* represents the CO_2 total annual gain.

The development of the algorithm

Biomass and soil carbon balance within the CO_2RCA algorithm

The core objective of the algorithm is to provide an efficient and accurate estimation of the capacity of tree crops to remove CO_2 from the atmosphere. This is achieved by estimating the CO_2 balance between atmospheric removal associated with the formation of new biomass, carbon stored in soil, and emissions released to the atmosphere through applied agricultural practices. The algorithm evaluates the annual removal capacity (ARC) according to Eq. 1. The CO_2 removal component linked to the new biomass production, captures changes in biomass (ARB), as a result of: (a) the production of fruits (AR_f); and (b) the development of the trunk, branches and roots of the tree (AR_w). Thus:

$$ARB = AR_f + AR_w \tag{2}$$

More specifically, the fruit biomass is calculated as a function of the total yield of the farm, the density of the tree crops cultivated and the relevant surface of the farm. The yield might also be increased through the application of alternative agricultural practices, and this is included as a coefficient in the calculation. The wood biomass on the other hand, which includes new trunks, branches, and roots, and quantifies the CO_2 that is annually absorbed by the tree, is evaluated as a function of planting density, the surface of the tree crops cultivated and the annual rate of biomass growth. This growth rate varies according to the age of the tree. So, in our approach, two development periods are considered, the Juvenile phase and the Mature phase, each one of which defines a different constant development rate (i.e., linear increase). We consider the Juvenile phase as the initial stage of planting the tree, and until it reaches the full production period. It then moves into the Mature phase with a slower development rate. The biomass changes described are corrected by the amount of annual pruning residue which can be left on the field (contributing carbon to the soil input), can be burnt (returning the CO_2 to the atmosphere), or has another use.

Modeling soil organic carbon dynamics (RothC approach)

The dynamics of carbon in soil are simulated using the RothC model (version 26.3) and by using monthly steps to calculate soil organic carbon. In the RothC framework (Coleman and Jenkinson 1996; Coleman et al. 1997), the Soil organic carbon (SOC) is modeled by four active connected pools and an inner organic matter pool (IOM). The four pools are the Decomposable Plant Material (DPM), the Resistant Plant Material (RPM), the Microbial Biomass (BIO) and the Humified Organic Matter (HUM). The amount in each pool decomposes according to first-order kinetics at its own rate. So, the incoming carbon (in our case, fruit from thinning processes, leaves, and pruning left on the field) is split between DPM and RPM based on the DPM/RPM ratio. All the incoming carbon passes through these polls only once. Then, DPM and RPM decompose to CO_2, BIO and HUM. The proportion of DPM and RPM that goes to CO_2 and to BIO + HUM depends on the soil characteristics (for example, clay content). Finally, BIO HUM further decomposes to CO_2, BIO and HUM and so on. The overall decomposition rate on the active pools is a function of temperature, moisture, and a constant decomposition rate specific to each pool. The data required to set the parameters of the model are the climatological data and the soil characteristics.

Estimation of emissions and mitigation gains

The cultivation practices contribute to the emissions (TAE) in three dimensions. The first is the use of fertilizers, the second is the use of pesticides, and finally the consumption of fossil fuels (gasoline and diesel) and electricity. These represent the use of mechanical equipment and machinery – powered by internal combustion engines or electricity – across a range of cultivation activities (tillage, trimming, spraying, irrigation, harvesting, etc.). The calculation of emissions associated with fertilizers (and pesticides) is influenced by the chemical composition and the quantity used, as well as an emission factor that accounts for carbon-equivalent emissions generated during the production, transportation, storage, and application of each component. A similar approach is adopted for gasoline, diesel and electricity where each emission is based on: annual consumption, an emission factor regarding greenhouse gas emissions due to production and combustion (in the case of gasoline and diesel), and the surface of the tree crops. Detailed formulations of emission components and mitigation gains from specific practices (including parameter definitions and numerical examples) are provided in Appendix B.

Operationalization, data sources and measurement methods

The calculation boundaries and the relevant timeframe are confined to the tree and the tree-crop land of the farm. The time span considered is a full calendar year, as it encompasses the complete productive cycle of the tree crop within this period. The CO_2RCA is integrated into a web-based e-tool, named the "Tree Crops CO_2 Removal Capacity Calculation Tool (CO_2RCCT)", available at https://climatree.uehr.gr, designed to accommodate users with varying levels of knowledge and information. To support its functionality, an extensive database has been incorporated, containing relevant data and coefficients suitable for use in the CO_2RCA equations, as summarized in Table 2. The tool also offers flexibility for users to input custom variables when more specific or locally verified data are available, enhancing adaptability across diverse contexts. To ensure methodological consistency, all emission factors and coefficients adopted in the CO_2RCA are aligned with IPCC Tier-1 methodologies and compatible with the most recent European reporting frameworks (IPCC, 2019; EEA, 2024). Older LCA-based references (Green, 1987; Audsley et al. 2009) were retained where their values remain broadly consistent with current IPCC uncertainty factors.

To ensure accurate calibration and transparency, field data were collected within the LIFE ClimaTree project to support validation of the CO_2RCA algorithm. Field measurements were undertaken in representative orchards in Basilicata (Italy), complemented by field experiments conducted by the Agricultural University of Athens (AUA) in Central Greece. These campaigns covered the five studied tree crops (olive, orange, peach, apple, and almond), focusing on biomass sampling of fruits, leaves, branches, weeds, and roots to estimate above- and below-ground carbon stocks. Soil samples were collected from the top 0–30 cm layer for determining organic carbon concentration, following IPCC (2006) guidance, and were used to parameterize the RothC 26.3 soil carbon model together with regional climatic data (2008–2012). Emission data were compiled from on-farm records of fertilizer, pesticide, fuel, and electricity use, and converted to CO_2-equivalents using Greenhouse Gas Protocol (2015) factors. These measured observations, combined with national statistics and literature sources, provided the empirical basis for validating the algorithm across Greece, Italy, and Spain, thereby enhancing the scientific transparency of the CO_2 balance assessment.

Additionally, national statistical data have been used for the yield, plant density, and cultivated areas, whose values are defined as the average value for the years 2012–2016. These values, as well as all the other characteristics noted on the above table, can be updated through the back-end of the e-tool. The annual rate of tree biomass development is defined for both the juvenile and mature growth phases, while fruit production levels and pruning amount are derived from state-of-the-art literature and calibrated and verified through extended field measurements for the first five tree crops in three countries. The climatological historical data which are used include monthly rainfall, open pan evaporation, and average air temperature. The soil characteristics refer to the clay content on topsoil and it is adopted from the LUCAS TOPSOIL dataset.

Management scenarios for cultivation practices

To estimate the impact of various cultivation practices on the carbon balance of tree crops, three distinct management scenarios were developed: Business as Usual (BAU), Medium, and Mitigation-Rich Practices (MRP). These scenarios reflect increasing levels of adoption of sustainable practices and allow for a comparative assessment of their CO₂ removal potential. Each scenario consists of a feasible and internally consistent set of agronomic techniques, varying in their expected effects on inputs such as fertilizers, water, pesticides, and fuel. Table 3 provides an overview of the core practices characterizing each scenario.

The quantitative assumptions underpinning the Medium and Mitigation-Rich Practices (MRP) scenarios are based on the analytical review conducted within the LIFE CLIMATREE project (Best Available Practices Guide for Tree-Crops Carbon, 2019). This review synthesised experimental data from a wide range of Mediterranean orchard studies for the tree species and countries considered in the present analysis. Specifically, fertigation practices were found to reduce nitrogen fertilizer inputs by approximately 15% and diesel consumption by 5–20%, while mulching improved soil moisture retention and decreased irrigation water and electricity use by about 30%. The use of leguminous cover crops was associated with 10–20% lower synthetic nitrogen requirements and pruning residue valorisation was shown to substitute part of the diesel energy consumption through solid biofuel production. These harmonized percentage modifiers were applied consistently across all study countries to maintain comparability, acknowledging that local agro-climatic factors may lead to slight differences in practice efficiency.

Table 3 Description of the three scenarios involving different management practices

Scenarios	Management practices	Brief Description
1 = BAU	- Conventional fertilizer and pesticide use	Application of fertilizers and pesticides in the selected tree crops without the adoption of alternative management practices
2 = Medium	- Use of cover crops - Implementation of fertigation	This scenario simulates the insertion of cover crops and the application of fertigation to all tree crops. Fertigation is expected to reduce the quantity of fertilizers used on average by 15% and diesel consumption ranging from 5 to 20%. The use of cover crops is likely to reduce pesticide and fertilizer consumption.
3 = MRP	- Use of Leguminosae cover crops - Application of mulching - Application of insect monitoring and mass trapping - Utilization of pruning residues as a solid fuel substitute for diesel.	Mulching can achieve a 30% reduction on the consumption of irrigation water and therefore the same reduction on electricity demands. Pruning management can reduce diesel consumption.

BAU= Business as Usual; MRP=Mitigation-Rich Practices

Regional mitigation potentials and their economic benefits

The CO_2RCA algorithm was then used to calculate the aggregate CO_2 removals on an annual base for the selected tree crops across the NUTS 3 regions in Italy, Greece and Spain. These results can also be aggregated at broader territorial levels, namely NUTS2 and NUTS1. The estimates reflect both CO_2 balance under the current cultivation practices, as well as the additional CO₂ removal potential induced by the selected management practices. In this context, removal potential is defined as the additional CO₂ removal capacity, calculated as the difference between mitigation-medium (Scenario 2) and mitigation-rich (Scenario 3) practices and the business-as-usual baseline (Scenario 1).

These estimates were integrated into a Geographic Information System (GIS) environment to generate comprehensive maps showcasing the aggregated mitigation potential of tree cultivations at a regional level for different management practice scenarios. These maps are likely to provide valuable insights into the geographic distribution and magnitude of the mitigation potential, supporting the design of geographically targeted mitigation policies and incorporating it into regional planning. Finally, a simple and practical method was employed for estimating the economic value of CO_2 sequestration (i.e., to assign monetary value reflecting the social welfare generated by this ecosystem service) by utilizing the prevailing market prices for traded CO_2. This approach was adopted to facilitate comparisons of potential economic benefits from carbon sequestration across different regions (and countries).

Sensitivity analysis

To provide a quantitative indication of the robustness of the estimated mitigation potential, a one-factor-at-a-time (OFAT) sensitivity test was conducted using the disaggregated emission components available in the LIFE CLIMATREE CO₂RCCT dataset. For three representative crop–country pairs (Greek olive, Spanish orange and Italian almond), we applied a ± 10% perturbation to (i) the fertilizer-related emissions (as defined in Eq. B1 in the Appendix), (ii) the emissions from other agrochemical inputs, and (iii) the emissions from fuel and electricity use, while keeping all other parameters constant. The resulting percentage change in total emissions for each perturbation was then propagated to the annual CO_2 Removal Capacity potential (induced by the application of mitigation-rich practices) to quantify the effect on net mitigation outcomes. The full procedure and detailed results are provided in Appendix B (Table B2). This sensitivity analysis aims to test the robustness of comparative mitigation outcomes across crops, countries and management scenarios under plausible parameter variation, rather than providing a full uncertainty propagation of the CO_2 balance. Although uncertainty in individual emission factors is an inherent limitation of carbon accounting exercises, the results suggest that reasonable variations in key input parameters do not affect the relative magnitude or ranking of mitigation effects.

Results

Additional removal capacity under alternative management practices

To assess the effect of different cultivation strategies on carbon sequestration, the CO_2 balance was estimated under the three management scenarios described in Table 3: Business as Usual (BAU), Medium, and Mitigation-Rich Practices (MRP). These scenarios were developed in the Methods section to reflect increasing levels of sustainability in orchard management. The calculations of carbon balance and absorption in the three scenarios were implemented with the CO_2 Removal Capacity Algorithm (CO_2RCA). Data has been drawn from national statistics, extensive literature review, and extended field measurements in the three countries studied. The mitigation potential is presented in Table A1 in the Appendix, which reports the net annual CO_2 balance (removals minus emissions) per crop and per management scenario, expressed in t CO_2 ha^{-1} yr^{-1}. These values therefore represent *per-scenario net stock change*, expressed in t CO_2 ha^{-1} yr^{-1}.

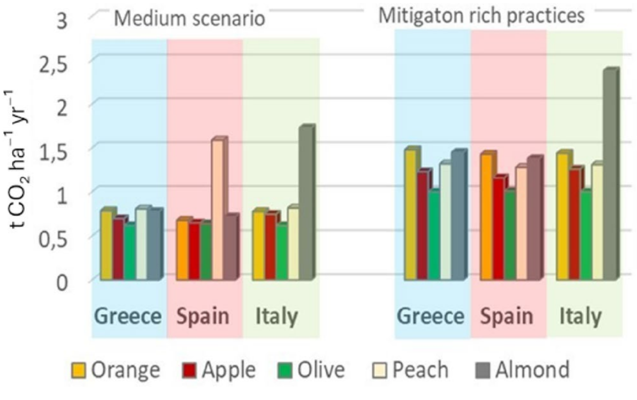


Fig. 2 Summary of the results in Table A1 (Appendix). Specifically, depicting the additional removal capacity (in t CO_2 ha^{-1} yr^{-1}) of Scenarios 2 and 3, as compared to the business-as-usual scenario (Scenario 1)

Figure 2 illustrates the *additional CO_2 removal capacity*, calculated as the difference between the mitigation-rich (Scenario 3) or medium (Scenario 2) scenario and the business-as-usual baseline (Scenario 1). It is evident that the efficiency of carbon sequestration varies among tree crops and agricultural management systems, and that distinctive patterns exist across the Mediterranean countries. As shown in Fig. 2, the implementation of mitigation practices results in an additional annual removal capacity ranging from approximately 1 t CO_2 ha^{-1} yr^{-1} (medium scenario, S2-S1) up to 2 t CO_2 ha^{-1} yr^{-1} (mitigation rich practices, S3-S1). Based on these findings, and considering the data constraints of this study, almond and orange crops exhibit the highest additional removal capacity compared with the other crops. The aggregate annual additional CO_2 removals (S3–S1), aggregated at the national level and disaggregated by tree crop, are presented in Figure A1 (Appendix A).

The robustness of these scenario-based estimates was examined through a simple one-factor-at-a-time sensitivity test (Appendix B, Table B2). A ± 10% variation in the underlying emission components (fertilizers, agrochemical inputs, fuel and electricity use) resulted in relatively small changes in additional removals: approximately 3–4% for olive and orange orchards, and 2–5% for almond orchards. These modest deviations indicate that the comparative outcomes across crops and countries are not sensitive to plausible parameter uncertainty and that the relative ranking of mitigation performance of Fig. 2 remains unchanged.

Regional mitigation potential of tree cultivations

The results were spatially integrated within a GIS framework to quantify aggregated additional CO_2 removal (t CO_2 yr^{-1}) at the NUTS-3 regional scale resulting from the adoption of mitigation-intensive practices. Maps were created using QGIS 3.34.3 (https://qgis.org/download/) under the ETRS89 / LAEA Europe projection (EPSG: 3035), consistent with Eurostat's regional data framework. Regional boundaries were obtained from the Eurostat GISCO/EuroGeographics NUTS 2021 shapefile, and crop-specific area data were derived from Eurostat Agricultural Statistics for orchard cultivations (2019). Olive tree cultivation constitutes the most extensive and socio-economically significant permanent tree crop in the Mediterranean region, particularly within the 3 countries examined. Therefore, spatially explicit results have been generated and illustrated for: (i) olive trees; and (ii) the other 4 tree crops, namely almond, apple, orange and peach.

Figure 3a illustrates the spatial pattern (per NUTS3 region) of the enhanced carbon absorption potential, expressed as additional CO_2 removals (S3–S1), for olive crops under mitigation-rich management practice. While the annual additional removal per hectare is broadly similar across the three countries (approximately 1 t CO_2 ha^{-1} yr^{-1}), substantial spatial variation is observed in the aggregate additional CO_2 removal at the regional level. These differences are mainly driven by the total area devoted to olive cultivation in each region rather than by per-hectare performance.

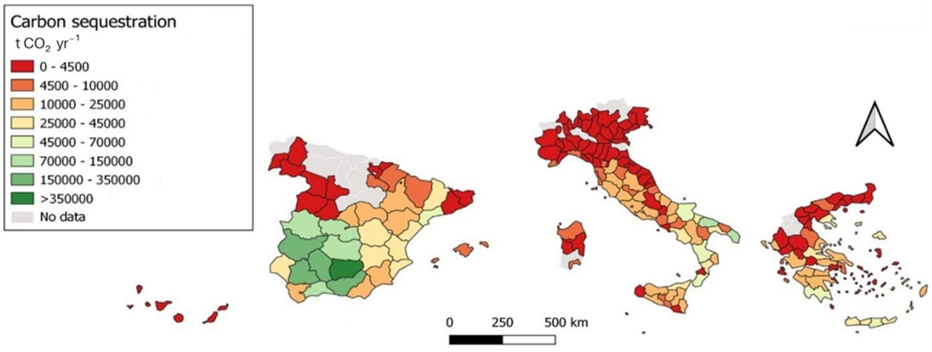
Across all three countries, northern areas characterized by fewer or smaller olive groves exhibit relatively moderate carbon sequestration potential and lower net benefit estimates than southern regions. The higher aggregated estimates observed for Spain can be attributed to the substantially larger average size of its NUTS 3 regions relative to those in Greece and Italy. At the national (NUTS1) scale, the additional aggregate CO_2 removal capacity is estimated at 810,000 t for Greece, 2,456,159 t for Spain and 1,133,821 t for Italy.

Figure 3b displays the spatial distribution of the annual additional removal capacity resulting from the potential implementation of mitigation-rich practices (Scenario 3) in the four remaining tree crop cultivations. Their spatial patterns of CO_2 removal indicate that eastern regions of Spain show the greatest divergence from the baseline scenario, exhibiting a higher sequestration potential. Importantly, several central and northern regions in Italy and Greece—where olive cultivation exhibits limited carbon sequestration potential under current conditions (Fig. 3a) due to less favorable climatic suitability – may still gain substantial ecosystem benefits by adopting climate-mitigating cultivation practices for these tree crops.

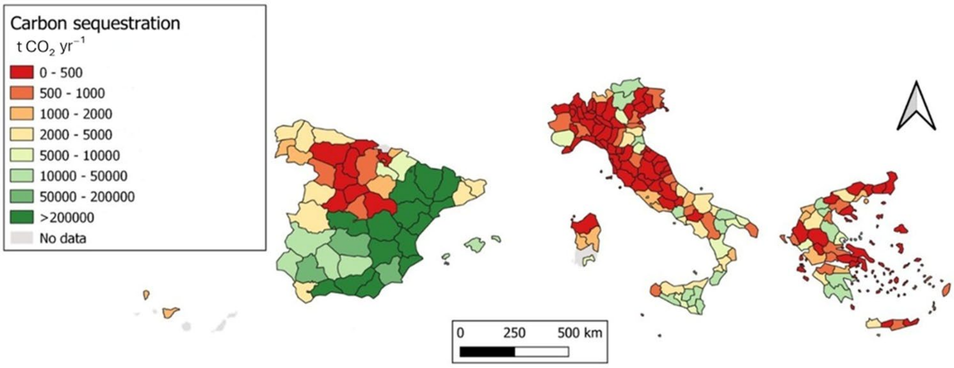
Regional economic benefits from applying mitigation rich practices in tree crops and country-level comparisons

To estimate the monetary value of the mitigation potential in tree crops, we first calculated the additional removal capacity gained by adopting mitigation-rich practices. Specifically, we determined the difference in annual CO_2 sequestration potential per hectare between the baseline scenario (Scenario 1) and the optimal scenario with best practices (Scenario

Fig. 3 Annual additional removal capacity (in t CO_2 yr^{-1}) of orchards per NUTS3 region

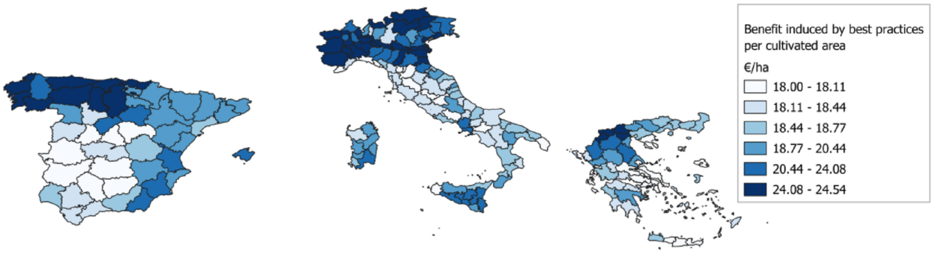


(a) Olive trees per NUTS3 region

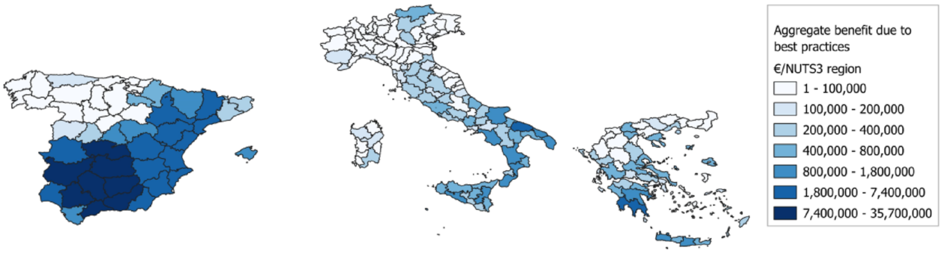


(b) Other trees (almond, apple, orange, peach) per NUTS3 region

Fig. 4 Economic value of carbon removal at the NUTS3 level: (**a**) per hectare value associated with adopting mitigation-rich practices, and (**b**) aggregate regional value based on existing tree-crop cultivation areas. Maps were created using QGIS 3.34.3 software tool (https://qgis.org/download/)



(a) Per hectare economic value of carbon removal induced by mitigation-rich practices (S3-S1), estimated at NUTS3 level



(b) Aggregate economic value of carbon removal induced by mitigation-rich practices (S3), based on existing tree-crop land use, at the NUTS3 level.

3). We then converted this (S3-S1) sequestration gain into monetary terms by applying an indicative carbon price of €30 t^{-1} CO_2, consistent with EU Emissions Trading System (EU-ETS) allowance prices around the time of project implementation (January 2021). Indicative allowance prices for EU ETS emission permits (EUA) were obtained from publicly available historical price series (e.g., TradingEconomics, ICAP, etc.), which show that prices have increased from approximately €30 t^{-1} CO_2, during the reference period to over €80 t^{-1} CO_2, in more recent years. The €30 t^{-1} CO_2 price is used to provide an order-of-magnitude valuation and to illustrate regional differences in economic outcomes and does not imply eligibility for compliance markets or pre-empt requirements related to additionality or monitoring, reporting and verification. For the purpose of this valuation, current land uses and prevailing cultivation practices were assumed to remained unchanged. This allowed us:

(a) to estimate the additional sequestration per hectare for each crop j and (NUTS3) region i, representing the difference in sequestration potential between Scenarios 3 and 1:

$$AS_{i,j} = ASbestpract_{i,j} - ASbaseline_{i,j} \tag{3}$$

(b) to convert this sequestration gain into monetary value by multiplying it by the CO_2 price (€30 t^{-1} CO_2):

$$MASV_{i,j} = AS_{i,j} \times 30 \tag{4}$$

(c) to aggregate the regional monetary value of CO_2 sequestration by considering the total area of each tree crop j within a region i:

$$RASV_i = \sum MASV_{i,j} \times X_{i,j} \tag{5}$$

where: $ASi_{i,j}$ is the (S3-S1) additional sequestration per hectare for crop j in region i (t CO_2 ha^{-1} yr^{-1}), $MASV_{i,j}$ represents the corresponding per-hectare monetary value (€ ha^{-1}), $X_{i,j}$ is the total area (ha) covered by crop j in region i and $RASV_i$ is the total regional economic value of CO_2 sequestration (€ yr^{-1}).

Maps were once again created using QGIS 3.34.3 software tool (https://qgis.org/download/). Figure 4a presents the spatial variation (ranging from 18€ ha^{-1} yr^{-1} up to 24.5€ ha^{-1} yr^{-1}) of the annual per hectare value-added estimates from adopting the best mitigation practices. Therefore, this map represents the spatial variation of the average additional economic value (per hectare of tree-crop area) that can be generated annually by adopting Scenario 3.

To determine the aggregate regional economic value (i.e., the total positive externality) of adopting the mitigation-rich practices, we multiplied the per-hectare addition sequestration value of each tree-crop by its corresponding cultivated area in each region, and the resulting values were then summed across crops (see Eq. 5). Figure 4b depicts the resulting aggregate value-added per region associated with the adoption of the best practices (Scenario 3).

According to Fig. 4a, the highest benefits (24.08–24.54 € ha^{-1}) are concentrated in specific regions of Northern Spain, Northern Italy, and some central and northern parts of Greece. On the other hand, Central and Southern regions of Spain and Italy generally show moderate benefits, reflecting varying levels of sequestration potential or adoption of best practices. These findings emphasize the importance of geographic and climatic factors in determining the economic value of sustainable practices, suggesting that regions with lower benefits may require targeted support mechanisms, such as eco-schemes, to encourage the adoption of such practices. The aggregate benefits map (Fig. 4b) highlights that Southern Spain, Southern Italy, and parts of Central and Southern Greece achieve the largest regional economic gains, with values ranging from €7.4 million to €35.7 million per NUTS3 region. This pattern suggests that extensive land use in these areas, combined with moderate per-hectare benefits, drives higher aggregate values. In contrast, Northern regions with high per-hectare benefits do not necessarily show corresponding aggregate gains, which is likely due to smaller cultivation areas.

Using a carbon price of approximately 30 $€t^{-1}$ CO_2, the adoption of best management practices is estimated to generate an aggregate additional CO_2 removal value of €2,176 million. However, it should be noted that CO_2 price assumptions vary markedly (Tang et al. 2016; de Souza et al. 2025; Schneider and McCarl 2006), while associated co-benefits are omitted. Our 30€ t^{-1} estimate is very conservative, notably lower than the EU-ETS average (≈ €70 t^{-1} CO_2 in 2024) and subject to market fluctuations (e.g. the EU-ETS price surpassed €100 t^{-1} CO_2in February 2023 and was trading around €90 t^{-1} CO_2 as of May 2023). This suggests that the actual value of this ecosystem service—the positive externality of tree crops—could be nearly two or even three times higher than the value indicated on the two maps (Fig. 4a and b). On the other hand, the economic estimates also assume full transfer of carbon value to land managers, whereas transaction costs and incentive design may reduce the share of benefits effectively realized in practice.

The economic valuation presented herein is intentionally indicative and policy-oriented, aiming to illustrate the order of magnitude of potential mitigation benefits. The aim is not to provide a full market feasibility assessment. Besides, carbon prices, certification requirements, transaction costs, and incentive design vary substantially across schemes and over time, introducing uncertainty in the net value effectively captured by farmers, the explicit modelling of which lies beyond the scope of the present analysis.

Discussion

Agriculture represents a significant source of greenhouse gas emissions, with implications for both environmental systems and society. Emissions generated within the farm gate rose by approximately 10% between 1990 and 2019, from 6.6 to 7.2 Gt CO_2eq (FAO 2021). In 2018, agricultural activities within the farm gate – when land use and land use change are also taken into account – generated an estimated 9.3 billion tons of CO_2 equivalent worldwide (CO_2eq) (FAO 2021). Without changes in current policies and considering current trends, agricultural GHG emissions are projected to grow by 4% between 2020 and 2030 (OECD/FAO 2021).

Nevertheless, the LULUCF domain could play a supportive role in enabling the EU to achieve its net-zero emissions target and fulfill the climate stabilization objectives outlined in the Paris Agreement. However, achieving these goals requires: (a) countries to strengthen their strategies (Perissi 2025), and (b) a reversal of the current declining trend in the EU's carbon sink (EC, 2024). Luo et al. (2024) report that Greece, Italy and Spain (among other EU countries), outline relevant policies but provide limited information on implementation mechanisms, impact quantification, and monitoring, resulting in uncertain pathways towards meeting the 2030 LULUCF targets. On the other side, projections from the European Environment Agency (EEA) for the period 2021–2030, the Mediterranean countries will continue along the same trajectory and may not succeed in reversing the trend (refer to Table A2 in the Appendix).

Considering the escalating emissions at the farm gate, it becomes imperative to adopt alternative agricultural management practices that not only reduce emissions but also enhance carbon removal. The implementation of carbon farming schemes, particularly in Europe and the Mediterranean region, holds significant potential as a long-term solution to address this challenge (Borrelli et al. 2016; Borovics et al. 2025). These schemes are designed to increase carbon sequestration and storage in agricultural landscapes while promoting sustainable farming practices and fostering sustainable land use practices. The forthcoming Common Agricultural Policy (CAP) can play an important role in this.

The crucial issue in this context is establishing a framework to facilitate agriculture-based mitigation. This framework involves two integral elements. Firstly, actual mitigation through scientifically validated methods must be accurately documented. Secondly, new incentives must be created to encourage farmers to explore the mitigation potentials of tree cultivation. Although the new CAP includes carbon farming in supported eco-schemes, significant gaps still exist. Recent contributions highlight the economic advantages of carbon sequestration, laying the groundwork for designing financial support mechanisms. Beyond policy-driven support mechanisms, this empirical evidence also suggests that market-based incentives may also play a complementary role. In particular, studies focusing on Mediterranean agri-food systems indicate that consumers may be willing to pay a premium for products with certified low carbon footprints, such as extra virgin olive oil, thereby creating additional economic incentives for the adoption of carbon farming practices (Bithas and Latinopoulos 2021; Regni et al. 2025). These findings highlight the potential relevance of consumer-driven demand in reinforcing policy objectives, although the explicit quantification of such mechanisms lies beyond the scope of the present regional-scale assessment.

In this context, the present study has developed a novel methodology that enables accurate accounting of the CO_2 balance of tree cultivations. The methodology evaluates, ranks, and demonstrates sustainable management practices in Southern Europe, with a focus on enhancing carbon sequestration and achieving a favorable CO_2 balance. It does so by highlighting the strong connection between the adoption of sustainable agricultural practices and CO_2 sequestration. The results of this study may support the design of a Monitoring, Reporting and Verification system as envisaged by the EU's Carbon Removal Certification Framework (CRCF) Regulation (EU/2024/3012). This framework establishes EU quality criteria and lays down monitoring and reporting processes to provide appropriate incentives to farmers (Holzleitner et al. 2024) and thus to facilitate investment in innovative carbon removal technologies and sustainable carbon farming solutions, while avoiding greenwashing.

Since the permanent biological nature of orchards resembles that of forests, orchards may offer significant carbon storage potential when properly managed (Sharma et al. 2021; Plénet et al. 2022). The perennial structure of orchards creates conditions for a more favorable net carbon balance, compared to annual crops, whose mitigation potential is limited to emission reductions. At the same time, the interpretation of carbon storage outcomes involves uncertainty, particularly with respect to the duration of carbon retention across different pools. The CO₂RCA framework estimates annual CO₂ balance and allocates carbon to pools with different retention characteristics. While carbon associated with woody biomass and soil organic matter is represented as longer-term storage within the annual accounting framework, it is not interpreted as permanent removal, as retention depends on management conditions and decomposition dynamics.

Given the strong influence of agricultural practices on orchard carbon balance, mitigation-rich management practices can enhance both carbon removal and storage capacity. Furthermore, these practices can generate additional positive effects on ecosystem services by enriching biodiversity, enhancing soil water retention and soil formation, and thereby strengthening the overall resilience of the agroecosystem (Lardo et al. 2018; Zanotelli et al. 2015; Prudhomme et al. 2020). Beyond ecological gains, agricultural-based mitigation also generates significant co-benefits for both society and the economy (Roe et al. 2021; McGuire et al. 2022; Demozzi et al. 2024; Holzleitner et al. 2024). Mitigation-rich cultivation practices use sustainable agronomic practices with lower chemical inputs, and less energy usage and provide yields of higher organic quality approaching the standards of organic farming. Consequently, this results in lower production costs and higher yield prices. Over the long term, these socioeconomic effects support the sustainable management of agricultural ecosystems, thereby enhancing the overall sustainability of rural areas.

Carbon farming is a knowledge-intensive process, requiring continuous exchange among farmers, scientists, and technicians, as well as the development of effective decision-support systems to guide implementation (Andrés et al. 2025). In this context, the methodology developed and embedded in the CO₂RCA operational algorithm serves as a practical decision-support tool for assessing how different management practices influence the CO₂ balance of tree crops. By quantifying both biogenic removals and management-related emissions within a unified framework, the approach enables consistent, practice-specific comparison of mitigation outcomes at the farm level and supports spatial aggregation of mitigation potential at the regional scale. These quantified impacts help to demonstrate the benefits of sustainable and mitigation-rich practices, thereby fostering behavioral change among land managers and informing the design of support mechanisms and incentive schemes.

Assessing the economic benefits associated with CO_2 sequestration offers a proxy valuation of this ecosystem service, which can facilitate its integration into operational policy frameworks. Consequently, financial instruments such as eco-schemes, introduced under the new Common Agricultural Policy, can be designed to incentivize farmers to implement farm-based mitigation measures. Recent analyses underline that the effectiveness of carbon farming schemes depends on a shift from activity-based measures, which reward the adoption of predefined practices, to result-based approaches, which compensate verified climate outcomes and incentivize measurable emission reductions (EC 2020; Thorsøe et al. 2025). This distinction underscores the relevance of tools such as CO₂RCA, which provide quantifiable, practice-specific estimates of carbon sequestration across farms, regions, and management scenarios, thereby aligning scientific assessment with emerging result-based policy frameworks.

Recent research demonstrates the critical role of geographical dimensions in carbon farming policy design and implementation (Colombo et al. 2024; Rosa et al. 2025), while EU recognizes that region-specific approaches are essential for effective carbon farming implementation by 2030 (Bumbiere et al. 2022). In this context, the geographical dimension of our findings is expected to be particularly relevant by: (a) informing national authorities in the design of suitable eco-schemes; and (b) setting environmental performance targets for priority regions where policy interventions should concentrate on enhancing the impacts of various cultivation practices. Specifically, the spatial disparities of potential economic benefits underline the need for tailored policy approaches. Policymakers could focus on regions with extensive land use for scaling up sustainable practices while leveraging the success of high-per-hectare benefit regions as models for best practices. Moreover, since these estimates are sensitive to EU-ETS prices, higher carbon pricing would significantly enhance the economic attractiveness of sustainable practices, potentially doubling or tripling current values. Addressing barriers such as upfront costs and lack of awareness in lower-benefit areas will be crucial for realizing the full potential of these practices.

Future research should explore how socio-economic factors and complementary ecosystem services, such as biodiversity, can further enhance the impact of sustainable agricultural practices. Future research should also focus on refining economic parameters and incorporating more comprehensive uncertainty and scenario-based analyses, in order to further enhance the robustness and policy relevance of carbon farming assessments. Emerging methods using UAV, LiDAR, and high-resolution satellite imagery show promise for improved tree biomass and carbon storage estimation (Brigante et al. 2025; Calisti et al. 2025) and could inform future enhancements of the CO_2RCA framework. Finally, the findings of our study may contribute to the upgrading of National Inventories concerning LULUCF sectors, a much-needed development that can support the design of accurate and informed climate policies.

Conclusions

This study introduces an operational methodology for assessing the CO_2 balance of Mediterranean tree crops, integrating biogenic removals, soil carbon storage, and management-related emissions through the novel CO_2 Removal Capacity Algorithm (CO_2RCA). By linking empirical data, spatial information, and emission factors, the approach offers clear and practice-specific assessments of mitigation outcomes. The results indicate that orchards managed under mitigation-rich practices, can deliver substantial carbon sequestration while providing co-benefits for biodiversity, soil quality, and rural sustainability. These findings highlight the role of perennial crops in supporting agricultural decarbonization and contributing to the EU's 2030 climate neutrality goals.

Beyond quantifying sequestration potential, the study provides a practical tool for integrating carbon farming into evidence-based regional planning and policy design. The spatial and economic outputs can guide CAP eco-schemes and result-based carbon farming incentives, ensuring that financial support mechanisms are linked to measurable outcomes rather than nominal practice adoption. Although some uncertainties remain - particularly regarding carbon pricing and benefit transfer assumptions - the proposed approach offers a replicable model for regional-scale valuation and for enhancing national LULUCF inventories. Future research could further strengthen carbon farming assessments by refining economic parameters, expanding the analysis to a broader range of crop types, and incorporating sensitivity and scenario analyses to further enhance the robustness and policy impact of carbon farming assessments.

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Author contributions K.B.: conceptualization, methodology, investigation, writing, research supervision, project administration, D.L.: methodology, writing, visualization, review and editing, I.S.: methodology, investigation, writing review and editing, A.S.: methodology, investigation, writing review, S.H.: methodology, investigation, writing review, P.R.: data collection and analysis, methodology, writing review and editing, G.M.: methodology, conceptualization, investigation, writing, E.E.: formal analysis, writing review, D.I.: methodology, conceptualization, investigation, writing review, A.M.: formal analysis and investigation, R-E.S.: formal analysis and investigation, E.T: formal analysis and investigation, K.P.: data collection and analysis, visualization, T.C.: reviewed methodology.

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Data availability The data that support the findings of this study are available from the Institute of Urban Environment and Human Resources (Panteion University), but restrictions apply to the availability of these data, so they are not publicly available. The data are, however, available from the authors upon reasonable request to the first author (Kostas Bithas).

Declarations

Competing interests 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.

Disclosure statement No potential conflict of interest was reported by the authors.

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