Evaluating Carbon Farming Practices for Sustainable Soil Management in Citrus Cultivation

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ABSTRACT

Oranges (citrus) stand out as a fruit of global nutritional and consequently commercial importance, serving as an important export product for many countries. Their cultivation in Mediterranean climates requires careful management of soil and water resources, where maintaining fertile and healthy soils is vital for ensuring productivity and fruit quality. Carbon sequestration in soils of citrus orchards represents a significant opportunity for climate change mitigation. The carbon sequestration potential of citrus trees lies in their ability to remove CO2 from the atmosphere and store it in their biomass and soil. Depending on how the soil is managed and what practices are applied, the tree's ability to sequester carbon is also affected. Studies reviewed in the context of the current mini-review, demonstrate that carbon sequestration agriculture such as cover cropping, reduced or no-tillage, pruning residue incorporation, and biochar / compost application significantly improve soil quality and can increase carbon sequestration. In addition, both biochar and compost, improve soil properties by increasing Cation Exchange Capacity (CEC) and balancing the pH, thereby enhancing nutrient availability for plants. These amendments aid in rehabilitating degraded soils, improve aeration and moisture retention, and support extensive root systems, which assist in carbon sequestration. Monitoring, Reporting and Verification frameworks are essential for enabling and incentivizing the application of carbon farming practices, and remote sensing technologies can provide valuable information for soil organic carbon (SOC) content monitoring over large areas. The current mini-review aims at discussing the potential of different practices for elevating SOC in citrus orchards and the potential applications of using remote sensing to monitor SOC levels in citrus orchards.

Keywords: Carbon farming, soil quality, carbon sequestration, citrus cultivation, sustainability, carbon storage

INTRODUCTION

The European Union (EU) aspires to become climate neutral by 2050 and has actively adopted binding laws and Strategies to achieve the aspiring target, with the EU Climate Law (Regulation (EU) 2021/1119) being a notable example. The LULUCF sector (Land Use, Land Use Change and Forestry) is emerging as critical sector for carbon removals because of its potential for carbon sequestration. The LULUCF Regulation (EU) 2023/839 aims at increasing carbon sequestration in agricultural lands, with the ambitious goal of greenhouse gas emissions not exceeding greenhouse gas removals by 2025 and the EU being able to remove 310 million tons of CO_2 yearly by 2030. Cyprus must remove 353 kt of CO_2 yearly by 2030, which represents a 20% increase compared to the 2016-2018 base values. In this context, the Common Agricultural Policy supports the targets of LULUCF Regulation, acting as a supporting force for the adoption of carbon-conscious agriculture through its various ecological and agri-environmental schemes. Furthermore, the Carbon Removals and Certification Regulation (EU) 2024/3012(CRCF), establishes the first standardized certification framework for verifying and recognizing carbon removals, supporting the LULUCF Regulation. The CRCF is expected to accelerate the creation of a voluntary carbon credit market in agriculture, providing farmers with financial incentives and market opportunities to implement carbon farming practices on their land.

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Citrus is a globally important fruit crop, with worldwide production reaching 169 million tonnes in 2023, with ca. 41.2% oranges, 31.0% tangerines, mandarins, and clementines, 14% lemons and limes, 5.9% pomelos and grapefruits and 7.9% for other citrus fruits [1]. The total harvested area is over 10.55 million hectares globally [1]. The production of citrus in the EU in 2023 was 10 million metric tons with a total acreage of 521,161 hectares [2]. The EU citrus production is concentrated in the Mediterranean region with Spain and Italy the leading countries, followed by Greece, Portugal, and Cyprus[2]. In Cyprus, citrus cultivation reached on average 3.000 hectares in 2023. In 2023, approximately 51,000 tonnes of clementines, lemons, mandarins, oranges and satsumas were produced [3] with exports reaching over 12 million euros [4, 5].

Citrus production in many areas, including the Mediterranean, a main citrus-producing region, faces significant environmental and agronomic challenges [6]. The evolution of management practices, often based on monocropping, intensive tillage, lack of cover crops, and excessive use of chemical inputs has frequently led to these agroecosystems being associated with degraded soils. Importantly, agricultural soils play a critical role in the global carbon cycle and greenhouse gas emissions, particularly CO_2 from soil respiration. Converting natural ecosystems to agriculture has generally reduced carbon storage [7].

Soil organic carbon (SOC) serves as an indicator of carbon sequestration dynamics. SOC is vital for soil fertility and a key component in the global carbon cycle. Healthy soils support food production and provide essential ecosystem services including biodiversity, biogeochemical cycle regulation, carbon sequestration, and water conservation [8]. The sequestration of carbon in the soil through conservation agriculture practices is identified as one of the most viable ways to reach carbon neutrality and mitigate climate change [9]. Therefore, transitioning to agriculture based on agroecological principles and adopting sustainable soil management strategies is essential to harmonize economic profitability and environmental conservation in citrus orchards.

This mini review evaluates various carbon farming practices in the framework of the CARBONICA project, specifically in citrus, to understand their potential for carbon sequestration and contribution to overall sustainability and exploring their impacts on soil health. The potential of organic amendments such as biochar and compost application for enhancing soil properties and carbon sequestration in citrus soils is evaluated. Finally, the broader environmental impacts of the practices is addressed, along with identifying existing research gaps and suggesting future directions. In addition, we provide a short discussion of the application of remote sensing methods for SOC estimation.

METHODOLOGY

This mini literature review aimed to explore the current state of knowledge on citrus cultivation and its connection to carbon farming practices, with a particular focus on their role in carbon sequestration. The objective was to assess whether these practices contribute to increased SOC levels and overall soil health. A literature search was conducted covering the period from January 1st, 2020 to May 28, 2025 using the Web of Science. The search combined the terms “citrus” and “carbon farming” or “carbon sequestration” and “biochar,” or “compost,” or “cover crops,” or “no tillage.” These combinations helped narrow the scope specifically to carbon farming practices relevant to carbon sequestration within citrus systems. The search yielded a total of 62 papers. Papers were shortlisted based on their relevance to field-based practices, rather than studies on industrial by-products. Consequently, from the initial search pool, 20 papers were selected for detailed analysis. Meta-analysis papers were not included in the current mini-review. Studies focused solely on producing biochar from citrus peels or applying it to non-citrus soils were excluded, as they fell outside the scope of the review.

RESULTS AND DISCUSSION

The papers included in the current work highlight the mechanisms by which carbon practices improve soil health and carbon stocks. Almagro et al. [10] assessed the impact of different inter-cropping practices on SOC storage and stabilization in an irrigated mandarin system under semiarid conditions, using a mandarin monocrop as the baseline. Compared to the mandarin monocrop, inter-cropping with an annual crop rotation resulted in SOC mineralization rates reduced by 30% at both the 0–10 cm and 10–30 cm soil depths after three years. Conversely, inter-cropping with a triennial crop rotation led to a significant reduction of 38% in the topsoil (0–10 cm) SOC stock compared to the monocrop, although the subsoil (10–30 cm) SOC stock did not differ. This topsoil SOC loss is likely attributed to increased tillage frequency compared to the monocrop, which disrupted soil aggregates, combined with limited new carbon inputs because the intercrops were harvested. Furthermore, both inter-cropping treatments caused significant reductions, ranging between 24% and 66%, in the organic carbon and nitrogen contents associated with soil aggregates in both the topsoil (0–10 cm) and subsoil (10–30 cm) compared to the mandarin monocrop system [10]. This result is attributed to the distinct management practices used in these irrigated systems, mainly the increased frequency of tillage and the harvesting of secondary crops instead of incorporating them as organic inputs [10]. Another experiment in Italy, assessed soil health by quantifying chemical, biological, and biochemical soil parameters under three different management models: abandoned, extensive, and intensive cultivation [11]. The authors quantified soil organic carbon sequestration primarily by measuring Total Organic Carbon (TOC) content in the topsoil (0–20 cm depth). The amount of TOC in abandoned groves was 2.69%, in extensive groves 2.80%, while in intensive groves 1.91%. The work suggested that intensive management reduced TOC levels compared to abandoned and extensive systems for citrus groves [11]

A 2024 study at an open-air commercial farm in Spain, evaluated the short-term effect of different management practices in the alleys of a grapefruit orchard, specifically comparing conventional tillage, no tillage, and alley cropping with the aromatic species *Rosmarinus officinalis* and *Thymus hyemalis* over a two-year period [12]. Soil CO_2 emission rates were measured, with generally higher emissions in the conventional tillage plots compared to the alley treatments, with *R. officinalis* alleys having higher emission rates than *Thymus hyemalis* and the tillage/no-tillage alleys. The higher emission rates in alley crops, are likely due to greater root development and microbial activity in the rhizosphere of the alley crops compared to the tilled or no-till bare alleys. The low content of SOC and low microbiological activity in the alleys were suggested reasons why tillage did not lead to higher overall CO2 emissions compared to no-tillage. The *R. officinalis* alley significantly increased SOC content over time, from an initial 1% to 1.2% after two years, indicating increased SOC sequestration compared to *Thymus* and the other alley treatments that remained close to 1% [12].

Pesce et al. [13] used a modified RothC model and field work to model the effects of rice straw mulching on SOC. The experiment was conducted in two citrus orchards in Valencia, Spain. Over the 2-year period of the experiment, model results predicted that mulch treatments resulted in a faster increase in SOC, estimating increases of 10.7 t C ha^{-1} and 18.7 t C ha^{-1} in mulch plots, compared to 2.1 t C ha^{-1} and 4.9 t C ha^{-1} in bare treatments, respectively. The model's successful simulation of the short-term experimental trends provides the basis for the longer-term projections made by the calibrated model. Based on its successful simulation of the experimental trends, the calibrated model projected that, on average, mulching could increase SOC stock by 62.16 t C ha−1 by the year 2050, potentially leading to a total sequestration of 9.88 Mt C across citrus orchards [13]

A one-year field study compared conventional tillage, no-till with intercropping of grass, mulch-till with straw covering, and minimum tillage in citrus [14]. After rainstorm events, the authors measured and collected surface runoff and subsurface leachate to determine nitrogen concentrations and calculate total nitrogen losses. The results showed that total nitrogen losses from the no-till plots were less than the conventional tillage plots by 19.03 kg N ha^{-1} $year^{-1}$, while minimum tillage plots saw a reduction in loss of 6.33 kg N ha^{-1} $year^{-1}$ compared to conventional tillage. Overall, no-till was the most effective treatment in reducing nitrogen losses from both surface runoff and subsurface leachate treatments[14].

A 17-year-long study in a salinity-affected lemon tree orchard in southeast Spain was run to assess the effects of intensive tillage with flood irrigation, (ii) no-tillage with pruning residues as mulch and drip-irrigation, and (iii) reduced tillage with incorporated pruning residues and drip-irrigation [15]. The reduced tillage system significantly improved soil properties compared to intensive tillage, with lower salinity (SAR - Sodium Adsorption Ratio decreasing from 1.1 to 0.1) and bulk density (decreasing from 1.6 to 1.1-1.2 g cm^{-3}), alongside increases in macroaggregate stability (MWD -Mean Weight Diameter, from 0.2-0.3 to 1.5 mm). Importantly, reduced tillage resulted in SOC stocks increasing by 82.3 % at 0-5 cm and 95.2 % at 5-15 cm compared to intensive tillage [15]. Another group of researchers conducted a 13-year comparison between conventional and regenerative management practices in two Sicilian orange groves [16]. They used a combination of Life Cycle Assessment (LCA) for calculating the carbon footprint and the SALUS (System Approach for Land Use Sustainability model) crop model for determining SOC sequestration or loss, integrating these results to calculate the overall carbon balance of each system. They found that the conventional system had a carbon footprint of 4.21 Mg CO_2-eq ha^{-1} yr^{-1} and lost SOC at a rate of 1.23 Mg CO^2-eq ha^{-1} yr^{-1}, resulting in a positive carbon balance of 5.44 Mg CO_2-eq ha^{-1} yr^{-1}. The regenerative system, however, had a significantly lower footprint of 1.07 Mg CO_2-eq ha^{-1} yr^{-1} and sequestered SOC at a rate of 1.68 Mg CO_2-eq ha^{-1} yr^{-1}, leading to a negative carbon balance (acting as a carbon sink) of −0.61 Mg CO^2-eq ha^{-1} yr^{-1} [16].

Another study compared the photosynthetic physiology of citrus plants grown under no tillage and sod culture across different seasons and various light intensities in central Taiwan [17]. The researchers measured a range of photosynthetic parameters, including net photosynthesis rate, stomatal conductance, electron transport rate, and chlorophyll fluorescence metrics. They found significant seasonal variations and differences between the tillage methods; for instance, the dark respiration rate of CO_2 was significantly higher in fall and winter (0.71~0.95 μmol CO2 m−2 s−1) compared to spring and summer (0.38~0.64 μmol CO2 m^{-2} s^{-1}). The maximum net assimilation of CO_2 was greatest under sod culture in spring (11.38 μmol m^{-2} s^{-1}), whereas it was lowest under no tillage in summer (5.21 μmol m^{-2} s^{-1}) and winter (5.61 μmol m^{-2} s^{-1}) [17]. In another study in Spain [18], where the inter-row soils typically suffer from fertility loss due to machinery traffic and herbicide use, researchers set up three management methods for the inter-rows: keeping the soil bare using herbicides (control), allowing spontaneous plants to grow, and planting fescue as a cover crop. The study monitored several physical, chemical, and biological soil properties. SOC did not show significant differences among treatments. However, SOC increased during the monitoring time in all treatments: spontaneous plants showed the highest increase (+47%), followed by fescue (+30%), and bare soil (+17%) from the first to the last sampling. The exchangeable potassium was significantly higher under the combined bare and spontaneous treatments than under fescue, with potassium higher in the spontaneous plant treatment compared to bare soil. Soil nitrogen showed no significant differences among treatments. Available phosphorus also showed no overall treatment differences, but the spontaneous plant treatment had significantly lower available phosphorus than the bare soil in three of the last four sampling times [18]. In another study [19], cover crops were planted in the inter-row middles of two Florida citrus orchards over three years, comparing them to a standard weedy control. In one citrus orchard, where cover crop establishment was high, soil organic matter (SOM), a key indicator of soil carbon, significantly increased in row middles from approximately 2.7% in the control to about 3.2% in the cover crop treatments, reflecting an improvement in soil carbon content. In contrast, in the other citrus orchard no significant differences in SOM were detected after three years, likely due to poorer cover crop establishment [19].

Castellano-Hinojosa *et al.* [20] investigated the depth-dependent effects of legume + non-legume or non-legume cover crops versus a grower standard in another Florida citrus orchard. The authors used as control traditional weedy row middles with spontaneously growing annual weeds common in South Florida, which were managed by mowing. They found that cover crop impacts on soil properties, nutrient cycling, gas emissions, and microbial communities primarily occurred in the top 0-10 cm soil layer. Planting legumes with non-legumes significantly increased soil NH_4^+ concentrations, net nitrification rates (~0.6 μg NOx g dry $soil^{-1}$ day^{-1} in legumes and non-legumes versus ~0.35 μg NOx g dry $soil^{-1}$ day^{-1} in the non-legumes and the grower standard at 0-10 cm) and N mineralization rates (~1.8 mg N kg dry $soil^{-1}$ day^{-1} in legume + non-legume versus ~0.4 mg N kg dry $soil^{-1}$ day^{-1} in grower standard at 0-10 cm, 80% water-filled pore space). Both cover crop mixes led to significantly greater SOM and permanganate oxidizable carbon (POXC) concentrations in the top 0-10 cm layer compared to the grower standard (e.g., legume + non-legume resulted in 3.6% SOM vs 3.2% for grower standard; non-legume 498 mg kg^{-1} POXC vs 400 mg kg-1 for grower standard) [20].

Qasim *et al.* [21] found that extensive farming management (characterized by low input requirements, minimal mechanization, and practices like retaining soil cover and incorporating organic amendments) was more effective at preserving soil functions and total organic carbon (TOC) compared to intensive cultivation or abandonment. The mean TOC level in citrus topsoil was 2.80% under extensive cultivation and 1.91% under intensive cultivation. A 2.0% threshold was considered as poor soil fertility condition [21]. In addition, another research study, evaluated citrus orchards under tillage, herbicide use (conventional), and organic managements, which included practices like vegetation cover between trees and chipping/spreading pruning residues, and found that the organic field had overall better soil physical quality with 67% of plant-available water capacity values classified as "good" (≥ 0.20 m^3 m^{-3}) compared to only 10% for the other two management practices [22]. The organic field also had a 5.0 and 2.8 times higher steady-state infiltration rate than herbicide and tillage plots, respectively, and an average total infiltrated depth of 276 mm, compared to 71 mm (herbicide use treatment) and 102 mm (tillage treatment), indicating superior water holding and transmission capacity. [22].

Ding *et al.* [23] investigated the effects of biochars derived from citrus peel and cassava stalks, pyrolysed at 500 °C, on soil properties and organic carbon mineralisation in citrus orchard soil samples under controlled laboratory incubation for 35 days, using application rates of 1%, 2%, and 4% [23]. The biochar applications significantly improved soil pH and available nutrients, with the 4% cassava stalk treatment boosting available phosphorus by 513% and available potassium by 1434%, and the 4% citrus peel biochar increasing available potassium by 1524% relative to the control. Both biochars substantially increased SOC content, reaching a 230% increase for the 4% cassava stalk treatment and a 179% increase for the 4% citrus peel treatment compared to the control. Furthermore, the cassava stalk biochar showed better carbon retention capacity, indicated by the lowest C0/SOC ratio (C0 represents the potential mineralizable carbon in the soil, with a lower C0/SOC ratio indicating a stronger soil carbon sequestration potential) of 0.169 at the 4% rate, compared to the control ratio of 0.302. Both biochar types effectively regulated soil pH to around 5.5, which is optimal for citrus growth. They explained that biochar alkalinity neutralizes soil acidity and the incorporation increases base cations [23]. In a similar study [24], researchers applied citrus peel biochar (OBC) and magnesium-modified citrus peel biochar (OBC-Mg) at rates of 0%, 1%, 2%, and 4% to citrus orchard soil and incubated the samples for 100 days to study their effects on soil organic carbon mineralization [24]. They measured various soil properties, including carbon mineralization, organic carbon fractions, physicochemical properties, and enzyme activities. Compared to the control, application of 1% OBC decreased cumulative soil organic carbon mineralization by 5.11%, and 1% OBC-Mg decreased it by 2.14%, suggesting a potential for carbon sequestration. OBC-Mg treatment was more favourable to increasing soil organic carbon fraction and content compared to OBC, with 4% OBC-Mg increasing SOC by 2.14 times compared to the control at the end of incubation. Furthermore, OBC-Mg significantly improved soil pH (increasing by up to 2.78 units with 4% application compared to the control) and enhanced the activities of soil enzymes like catalase (increased by up to 116.67% with 4% OBC-Mg compared to the control) [24].

Lavagi *et al.*[25]. investigated the potential of both bokashi and biochar, derived from agricultural waste, as sustainable soil amendments for citrus nursery production [25]. They conducted a greenhouse experiment applying bokashi, biochar or a combination at 10% v/v concentrations compared to a control soil mix [25]. The treatments were evaluated under two different fertilizer application rates (700 µS/cm and 1400 µS/cm electrical conductivity) to determine their effects on plant growth, soil health, and economic viability. The study reported several notable quantified changes compared to the control. Regarding nutrient content over 84 days, the bokashi 1400 treatment increased N content by 27.34%, P by 33.81%, and K by 16.47% on average. The combined bokashi and biochar 400 treatment showed even greater increases, averaging an increase of 64.49% for N and 106.33% for P. In a three-week analysis, bokashi 1400 increased the water content of the soil by 28.64% and bokashi 700 by 25.53% compared to the control. Additionally, the bokashi 1400 treatment demonstrated a substantial 41.55% increase in soil carbon content. The combined bokashi and biochar treatments also showed significant increases in the carbon content, at ca. 37.36% to 37.45% [25].

Bai *et al.* [26] prepared calcium-modified biochar from citrus fruit peels and applied it to citrus orchard soil at different rates (0%, 1%, 2%, and 4%) in a 100-day constant-temperature incubation experiment to investigate its effects on organic carbon mineralization, carbon fractions, and enzyme activities [26]. They observed that biochar significantly reduced the cumulative mineralization of soil organic carbon, specifically by 8.68% and 17.00% at 2% and 4% application rates, respectively, compared to the control. Higher application rates also led to an increase in SOC content, up to 1.32-fold with 4% biochar, and notable increases in active carbon fractions like readily oxidizable carbon, which saw a remarkable 108.59% increase at 4% biochar. Furthermore, biochar application significantly improved soil enzyme activities, with sucrase activity increasing by 216.42% to 393.44% across the 1%, 2%, and 4% treatments compared to the control [26].

In another study in China, Hu *et al*. [27] studied soil from a citrus orchard in a 30-day indoor incubation experiment. The authors added different proportions of orange peel biochar, created by burning citrus peels, and powdered *Cipangopaludina chinensis* shells, prepared from kitchen waste. The addition of the amendments significantly increased SOC content compared to the control, with increases ranging from 0.14 g kg^{-1} to 0.58 g kg^{-1} across different treatments at the end of incubation. Notably, the mixture of 2.6% orange peel biochar + 1.3% shell powder increased SOC by 19.81%, microbial biomass carbon by 64.88%, dissolved organic carbon by 67.81%, and readily oxidized organic carbon by 19.44% compared to the control. This combination also led to substantial increases in enzyme activities, including catalase by 77.55%, urease by 487.12%, and sucrase by 406.62% compared to the control [27].

Xia *et al*.[28] conducted a four-year pot experiment using acidic red soil and peanut shell biochar to investigate the effects of co-applying biochar (at 0% and 2% rates) and potassium fertilizer (at 0%, 60%, 80%, 100% of conventional rates) on soil K availability, organic carbon, citrus growth, and microbial functions [28]. The study found that the simultaneous application of biochar and conventional K fertilizer at 100% significantly increased soil available K content by 192.30% compared to the control treatment (no K fertilizer, no biochar) and enhanced SOM by 79.50%. Overall, the four-year co-application increased the availability of soil potassium by 2.9-fold and the storage of organic carbon by 1.8-fold. Furthermore, the combined treatment improved soil enzyme activities associated with carbon cycling by 31.9%–84.4%, enhanced microbial carbon source utilization capacity (for instance, carboxylic acids utilization was 44.0% higher with biochar addition), and resulted in a 35.2% increase in microbial functions responsible for labile carbon degradation in the biochar and K 100% treatment compared to control. The study also indicated that adding 2% biochar had the potential to replace 40% of conventional K fertilizer application [28].

Chen *et al.* [29] systematically explored the effects of biochar at different application rates in citrus production. The rates were 0 kg/plant as a control and 5, 10 and 15 kg/plant [29]. The authors reported that biochar significantly increased soil pH, organic matter, and CEC, as well as most nutrient elements. In the deep soil layer (20–40 cm), biochar increased pH by 0.2–0.3 units, raising it from an initial value of 3.8 to as high as 4.1. The 15 kg/plant treatment significantly enhanced soil organic matter content, increasing it from 49.1% to 64.5%, and boosted cation exchange capacity (CEC) by 24%, from 86.8% to 107.5%. Nutrient availability was also improved: available phosphorus (P) in the shallow soil (0–20 cm) increased by 51.7%–92.1%, while calcium (Ca) and magnesium (Mg) content increased by 56.6% and 125.9%, respectively, and by at least 125.7% (Ca) and 39.2% (Mg) in deep soil. These improvements were attributed to biochar's alkalinity, high carbon content, and surface functional groups that enhance nutrient retention and soil buffering capacity [29].

Studies confirm that compost application effectively increases SOM levels compared to control treatments. In pomelo cultivation in the Mekong Delta, applying compost over three years resulted in increased SOM compared to using chemical fertiliser only [30]. Specifically, in the sub-surface layer (20–40 cm), SOM content reached 4.12% with compost treatment, a significant increase compared to 3.04% in the control. Also, the compost treatments led to higher levels of exchangeable Ca^{2+} and Mg^{2+} cations in the treated plots. Compost treatment yielded a Ca^{2+} concentration 1.5-fold higher than the control treatment [30]. In another study [31] in orange groves, citrus waste used as an organic fertilizer was identified as a valuable material for reintegrating organic matter into the soil, with initial mean soil organic matter at 3.8% before amendment and initial organic carbon content ranging from 2.02% to 2.3% across treatments [31]. Hemdan *et al.* [32] investigated the use of *Moringa oleifera* seed cake and compost as organic soil amendments for cultivating Valencia oranges in Egypt over two seasons. Applying a mixture of moringa seed cake and compost at a 2:1 ratio proved most effective, leading to significant improvements in soil properties, leaf nutrient levels, fruit yield, fruit quality, and water productivity compared to untreated soil . [32] . For example, this treatment increased fruit yield by approximately 27-28% (from around 77 kg/tree to 98 kg/tree) and soil available water by about 66-70%. [32]

No-tillage and cover cropping applications are considered as conservation agriculture and can also enhance carbon sequestration, particularly in the surface layer [33]. The practices improve water retention, as maintaining ground cover or residues influences soil water content. For instance, conventional no-tillage using herbicides had negative impacts on soil health (no-tillage leads to soil degradation through organic matter loss, reduced biological activity, and increased erosion) compared to organic management which included no-tillage with vegetation cover (organic no-tillage with vegetation cover enhances soil health by increasing organic matter inputs and biological activity, improving soil structure, and reducing erosion) [9]. This suggests that no-tillage alone, especially in a conventional system relying on herbicides rather than organic matter input or cover crops, may show fewer benefits for parameters like SOM and aggregation, compared to practices that actively add organic carbon or maintain living cover crops. Cover cropping is used for maintaining vegetation cover and it is linked to improved soil physical quality, including water retention, and increased organic matter inputs that fuel microbial activity. These organic practices are a direct source of carbon and nutrients for the soil, contributing to SOM and providing substrate for soil microorganisms, thus enhancing microbial activity and nutrient cycling [33, 34].

In summary, work in citrus has shown that agricultural practices such as cover cropping, reduced or no-tillage, the incorporation of pruning residues, and the application of biochar and compost (organic amendments) significantly improve soil quality and increase carbon storage capacity in citrus cultivation [10, 25, 27, 28, 32]. These approaches are crucial for rehabilitating degraded soils, a common issue in intensive agricultural systems where practices like extensive tillage and excessive chemical input use have led to physical and chemical soil deterioration and erosion. In addition, conservation agriculture and organic amendments enhance soil aeration, increase moisture retention and improve water infiltration, and in many cases water holding capacity [17, 23]. Improved soil structure, reduced compaction and erosion and aggregate stability are also observed benefits [32, 35, 36].

In addition, the described conservation agriculture methods also promote increased microbial activity and microbial diversity, which are vital for soil functionality and nutrient cycling [19]. Increased enzymatic activity associated with C and N cycling is also enhanced by cover crops and organic amendments, including biochar [35]. While cover crops and pruning residues are valuable organic inputs that enrich soil organic matter and support microbial life, their impact might be perceived as moderate compared to biochar and compost due to differences in carbon stability and decomposition rates [37]. Much of the biomass from cover crops and pruning residues can decompose relatively quickly, depending on factors like C/N ratio, contributing to soil organic matter but potentially releasing more carbon as CO_2 in the short term [38]. Biochar, conversely, has a highly stable chemical structure that resists microbial breakdown, acting as a more durable, long-term carbon sink [39]. Similarly, compost provides concentrated, readily available nutrients and a diverse microbial boost [40], offering significant and often broader benefits to soil chemical properties like pH and CEC compared to the slower, less concentrated release from crop residues or cover crops upon decomposition.

For carbon farming practices to be effectively implemented and incentivized, robust MRV (Monitoring, Reporting and Verification) frameworks are essential. These frameworks must accurately quantify carbon removals, ensure additionality (that the sequestration would not have occurred without the intervention), and address concerns about permanence (the long-term stability of stored carbon) and leakage (unintended increases in emissions elsewhere) [41]. Monitoring SOC changes typically involves direct soil sampling and laboratory analysis. However, integrating remote sensing (RS) technologies offers the potential for broader spatial and temporal monitoring, providing valuable complementary data [42]. Generating carbon credits from agricultural carbon sequestration requires adherence to recognised verification standards. Such protocols typically involve establishing a baseline SOC level, implementing a rigorous monitoring plan, and demonstrating additionality.

Recently, many RS studies have focused on SOC quantification, with satellite data serving as an alternative solution either alongside or in lieu of laboratory and field data [43] [44]. Multispectral Sentinel-2 imagery [45] provides key data for assessing soil properties and conditions related to SOC and has been used for SOC prediction in croplands, with good performance [46]. However, accurately predicting SOC from remote sensing is often challenged by disturbing factors at the soil surface, such as photosynthetic vegetation and crop residues, variations in soil moisture, and surface roughness [47]. Dvorakova et al. [47] suggested that optimal conditions for spectroscopic analysis of SOC using Sentinel-2 occur when the soil is exposed and in a "seedbed condition", which occurs when residues have been ploughed in, the soil is smooth, and ideally dry. They suggested the use of composite images or temporal mosaics of images taken when the soil is at its most suitable condition for spectral analyses [47]. Mixed pixels, where part of a pixel covers the soil and another part vegetation is another significant challenge, as it disturbs the soil signal [48] [49]. Higher resolution images overcome the problem, but at a significant cost increase, as such images are not free. Hyperspectral sensors on satellites offer hundreds of bands enabling more detailed analyses for SOC, like for example the PRecursore IperSpettrale della Missione Applicativa (PRISMA) [50], EnMAP (https://www.enmap.org/mission/) both at 30 m resolution and more recently Pixxel (https://www.pixxel.space/) at 5 m resolution[51]. Petropoulos et al. [42] proposed a “System of Systems” approach, where sampling, sensing and modelling are integrated to provide acceptable estimates of SOC and promote carbon farming policies and practices.

CONCLUSIONS

The Common Agricultural Policy (CAP) plays a significant role in shaping agricultural practices and promoting environmental sustainability. Research quantifying the carbon sequestration potential of specific practices like pruning residue incorporation and compost application in citrus orchards can provide valuable evidence to inform the design and implementation of agri-environmental schemes under the CAP and globally. More research is required to assess the impact of these practices on soil physicochemical properties, carbon sequestration potential, and orchard sustainability. Potential work on this will provide insights for sustainable soil management and contribute to global efforts in mitigating climate change through carbon farming. Current work within the CARBONICA project focuses on experimental evaluation of compost and biochar addition in citrus plots of Phasouri Plantations, in Limassol, Cyprus. Assessing and monitoring SOC changes under the practices selected is crucial for carbon accounting and scaling up. Despite the clear benefits and development of assessment techniques, the widespread implementation of these practices and effective SOC monitoring face challenges. RS methods and traditional laboratory work provides an opportunity for improving MRV frameworks. Policies aiming to promote sustainable practices need to consider economic viability, potentially through incentives and subsidies. To move forward, future research should continue to conduct long-term field experiments to validate short-term findings and address uncertainties regarding carbon storage duration and soil respiration responses.

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