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How Much Organic Carbon Could Be Stored in Rainfed Olive Grove Soil? A Case Study in Mediterranean Areas

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Abstract: Agricultural activities generate CO_2, CH_4, and N_2O, affecting the global climate and the sustainability of agricultural production systems. This topic is essential in those areas where agriculture has caused soil decarbonization. The soil can regenerate by implementing sustainable soil management (SSM), and this regeneration is finite. Therefore, it is necessary to determine the maximum carbon (C) storage capacity to establish the most SSM for soil recarbonization. This research analyzes the C storage capacity in soils with rainfed olive groves and traditional tillage in the largest olive-oil-producing area in the world (Jaén, Andalusia, Spain). The results show that these soils had low soil organic C (SOC) content, ranging from 5.16 g kg^{-1} (topsoil) to 1.60 g kg^{-1} (subsoil) and low SOC stock (SOC-S) (43.12 Mg ha^{-1}; 0–120 cm depth). In addition, the SOC fractionation showed that the highest SOC concentrations were in the particulate organic C form. The SOC-S linked to the fine mineral fraction (<20 µm) in topsoil was 21.93 Mg C ha^{-1}, and the SOC-S saturated ranged between 50.69 and 33.11 Mg C ha^{-1}. Therefore, on the soil surface (0–32.7 cm depth), these soils have a C storage maximum capacity of 28.76 Mg C ha^{-1}, with a net C sink capacity of 105.55 Mg ha^{-1} of CO_2-eq. All this suggests that these soils could have a high recarbonization capacity, and applying SSM (in the coming years) could be an essential C sink.

Keywords: carbon stabilization; carbonization; soil mineral fraction; soil organic carbon saturation deficit; soil organic carbon sequestration potential; CO_2-equivalent

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1. Introduction

In the last years, different initiatives have emerged at the international level (4 Per Thousand, Adapting African Agriculture, Platform on Climate Action in Americas, Living Soils of the Americas, etc.), under which the soil has been highlighted as a carbon (C) sink [1,2], since soil organic carbon (SOC) can play an essential role in the global C cycle balance, affecting the greenhouse gas generation–mitigation [3,4]. In this sense, it is crucial to point out that the soils, together with the biotic fraction at a global scale, could have four times more C than the atmosphere [5], estimating that the first two meters of soil can store 2400 Gt C [6,7], and hence, slight changes in soil C could affect the global CO_2 balance [8]. The cultivated soils worldwide have lost between 25% and 75% of their original C reserves [3,9,10], which have been emitted into the atmosphere in the CO_2 form due to unsustainable management practices that lead to soil degradation, contributing to climate change. Consequently, soil degradation lowers the ability of soil to store C, contributing to global threats such as global warming, climate change, and the sustainability of agricultural production systems [11,12]. Given this situation, improving and increasing the soil capacity to sequester C is urgent and necessary, emphasizing agricultural soils since they are the easiest to control by humans [13]. Furthermore, increasing SOC is not only beneficial for mitigating climate change but also provides the restoration of the degraded soil with significant potential impacts on crop yields, food security, and the well-being of small farmers [12,14]; in fact, the SOC presence is a good indicator of soil quality [15].

In the Mediterranean basin, the olive grove (OG) is the primary land use [16], and Spain has the largest OG area in the world (2,584,564 ha). In addition, Andalusia is the region with the largest OG area in Spain (1,630,473 ha) [17], not forgetting that Spain produces the most olive oil globally (47%) [18]. However, this OG development affects the soil negatively since the vegetal cover in traditional OGs is low and favors the soil loss [19] conditioned by the slopes (pronounced in some cases) [20], with low organic matter (OM) contents (due to rapid changes in the precipitation and temperature regimes) [11,21] and influenced by conventional tillage (CT) (extremely aggressive with the soil) [11,22,23]. These factors acting synergistically have led to the loss of soil quality with economic and environmental implications [18,24]. So, the Mediterranean OG is related to degraded soils due to: (i) low aggregate stability [25], (ii) reduction in the soil infiltration rate [26], (iii) soil degradation structure [27], (iv) OM depletion, and (v) high soil loss due to water erosion [23], which leads decarbonization processes in soil [28]. In this sense, it is essential to note that CT has a negative effect on soil OM (SOM), negatively affecting C sequestration due to macroaggregate destruction and the acceleration of OM decomposition [27,29–32]. Conversely, conservation tillage helps to improve physicochemical soil properties [33], reduces soil erosion rates, supports adequate SOC levels [34], and increases soil fertility, soil structural stability, and soil biological activity [35].

In the last few years, interest in the feasibility, scope, and duration of SOC additional sequestration has increased rapidly [12,36] since the soil has a finite capacity to retain C (C saturation capacity); this means that once the soil is saturated, an extra C addition is not possible [37]. This C saturation in the soil is due to the SOC adhesion process to fine mineral particles. In this context, the fine structural aggregate formation (SOC + fine mineral particles) is considered one of the main SOC stabilization mechanisms in mineral soils [37,38], and assuming that the number of the fine particles (<20 μm: clay + fine silt) is limited, it is accepted that the soil can store stable SOC until these fine particles are neutralized. This upper limit may be considered the SOC saturation concept [15,38–40]. In this regard, IPCC [41] defined the SOC storage potential capacity as "the maximum gain of C from the soil (Mg ha^{-1}) that can be achieved in a given period due to land use and management changes". Therefore, the soil mineral fraction content [42] and the pedoclimatic conditions [43–45] are critical factors in the SOC storage potential.

One of the most accepted methods to establish the maximum soil capacity to store SOC on the soil surface (topsoil) linked to fine soil fraction (<20 μm) in temperate and tropical climates is the Hassink proposal [39]. This approach has been used in many countries with different land-use and management methods to determine the SOC storage potential [46–49]. In this context, we must bear in mind that Hassink's approach is a simplified proposal since it uses a single factor (fine silt + clay). In this line, different researchers [37,49,50] have indicated that for measuring the maximum soil capacity to store SOC, more elements should be used: e.g., mineralogy, pH, Ca content, climatic factors, etc. Therefore, determining the maximum SOC storage potential is difficult to achieve [50], so the different soil conditions prevent a homogenization of criteria. Accordingly, different methods would have to be defined depending on the soil type.

In light of all these considerations, we must differentiate between SOC sequestration (the long-term stabilized SOC associated with the fine soil fraction) and SOC storage (the SOC content including all SOC fractions) [51]. These terms should be complementary but show discrepancies among the scientific community [45] due to the different mechanisms of C stabilization and the time factor. They are different approaches, but at the same time, they should be complementary terms. However, regardless of the method used, what is important are the factors that can alter the entry and exit of C in the soil (the stationary C balance). Hence, it is essential to know the land management that increases the soil capacity to sequester C to prepare a work plan to lay the foundations of how much C we can store in these natural sinks and for how long [52].

Based on the previous considerations, the main objective of this research was to determine the maximum soil capacity to store C from soil organic carbon saturation capacity as an initial starting situation in an experimental farm of rainfed olive groves with conventional tillage to later (in the coming years) implement different management practices (crop diversifications) that improve and increase the SOC content. This initiative is part of the European Union's Horizon 2020 Programme for Research and Innovation (Diverfarming).

2. Materials and Methods

2.1. Description of the Study Area

The study was carried out in an experimental farm of 10 ha, with CT since the 1950s in Garcíez (Torredelcampo, Jaén) in the south of Spain (37°50′20″ N–3°52′32″ W) (Figure 1).

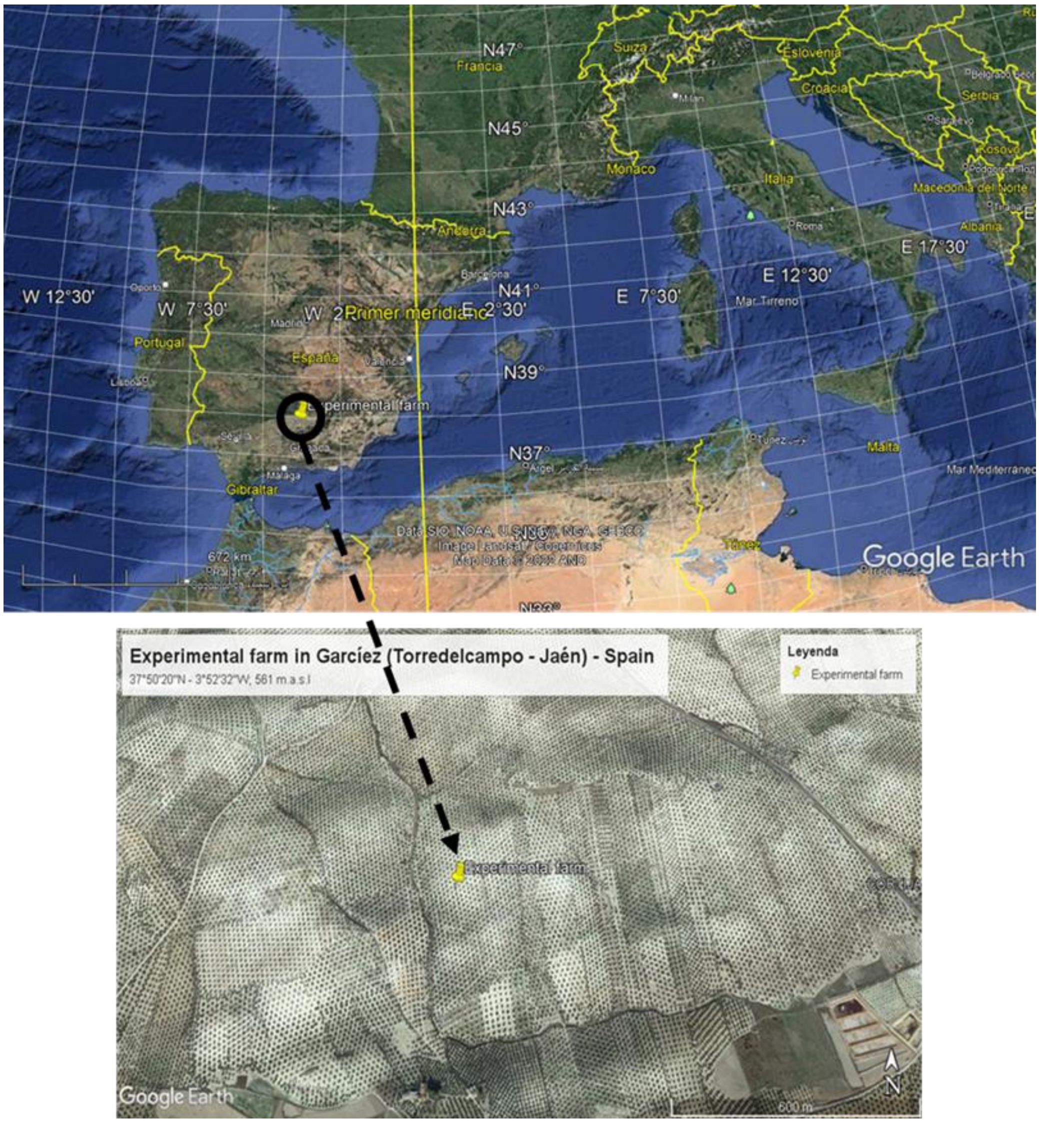

Figure 1. Study area. Garcíez, Torredelcampo (Jaén, Spain) (37°50′58.9″ N–3°51′55.9″ W). Source: author elaboration. https://earth.google.com/web/@38.75088885,-4.44622173,2424349.6930448a,0d,35y,358.9909h,0t,0r?utm_source=earth7&utm_campaign=vine&hl=es (accessed on 22 October 2022).

The land use was centenary rainfed OGs with CT (Figure 2), located at an average altitude of 561 m (ranging from 530 to 593 m), with slopes <5%. The soils in the experimental farm were calcaric Cambisols (CMca), according to WRB [53], characterized by low fertility, poor physical conditions, and low capacity for agricultural use [27,33,54].

Figure 2. Experimental farm with centenary rainfed OG of the Picual variety with conventional tillage farming. The image on the right is the farmer tilling the soil.

The parental material was Miocene loam and marlaceous lime [24], with denudation morphogenesis formed by hills [55]. Hydrologically, the study area was characterized by a dendritic network of carbonate facies, defined by: average annual rainfall of 493.2 mm, average yearly temperature of 17.1 °C (maximum temperatures of 46.2 °C in August and minimums of −7.8 °C in January), relative humidity of 59%, insolation of 237 h month^{-1}, wind speed of 6 km h^{-1}, humidity index of 0.50, rain erosivity ranging from 2.1 to 75, and 5 months with frost risks [56]. The climate is Mediterranean (Csa), with hot and dry summers (average duration of 3 to 5 months) and winters ranging from cold to cool, not too humid [57].

2.2. Experimental Design

The crop type in the study area was composed of traditional rainfed OG (centenary) of the Picual variety (*Olea europaea*), characterized by 90 trees ha^{-1} (two trunks per tree and a uniform tree spacing of 12 m × 12 m) and tree size (3 m high × 6 m canopy diameter), on a hillside with northeast topographic orientation (Figure 2). Over the years, this experimental farm has been extensively studied, described, and characterized [18,58].

The land management (Figure 2) was CT (heavily machined in the last decades and very aggressive with the soil), characterized by the following: Once the OG is harvested, mineral fertilization is applied (100 kg ha^{-1} of urea: 46% N) in alternate years. Later, the olive trees are pruned every two years, and the crushed pruning residues (6 Mg ha^{-1}) are added to the soil. After this, fungicides are applied (copper oxychloride 34.5% w.p.) to tree branches. In May, a disc harrow (25–30 cm deep) is used to remove weeds. In June, a cultivator is passed to break the soil's superficial crust and promote its aeration. Finally, in autumn, a broad-spectrum herbicide was added to control weeds under trees to allow the OG harvest.

2.3. Soil Sampling and Analytical Methods

According to GSOC-MRV Protocol [59], samples from 9 entire soil profiles were collected at the end of 2018 (initial situation—Diverfarming). Soil samples were collected along the different soil horizons for each profile. A random sampling scheme was adopted, pits were dug with a mini excavator, and samples were collected. Soil samples were placed inside polyethylene bags, labeled, transferred to the laboratory, and air-dried. Once dried, the samples were sieved with a 2000 µm sieve, separating the thick fragments and roots from the rest of the material. In addition, 3 replications were carried out for each sample in the laboratory. The analytical methods, laboratory analysis, and other parameters used in this study to determine different soil properties are reported in Table 1 according to the Handbook of Plant and Soil Analysis for Agricultural Systems [60]. The analytical methods used in this study were: bulk density (BD), according to the core method [61]; particle size distribution by the Robinson pipette method [62]; and total organic C according to the Walkley and Black method [63]. In addition, the soil was separated into five size fractions (>2000, 2000–250, 250–53, 53–20, and <20 µm diameter) [27,64], and 20 µm fractions were obtained [65–67], followed by extraction of labile dissolved organic carbon (OC) using a membrane filter and differentiating: heavy fraction (>2000 µm), particulate organic carbon—coarse POC (2000–250 µm), particulate organic carbon—fine POC (250–53 µm), mineral organic carbon—associated MOC (53–20 µm), and mineral organic carbon—dissolved MOC (<20 µm) [27,64–67].

The study was carried out on entire soil profiles by horizons, assuming the discrepancies (errors, biases) that can occur in the determination of the SOC saturation (SOC_{sat}) and the SOC saturation deficit (SOC_{def}) at depth since the Hassink proposal [39] is only for the topsoil.

Table 1. Analytical methods used in this study (field measurements, laboratory analysis, and parameters calculated).

Parameters	Method
Field measurements	
Bulk density (Mg m^{-3})	Core method [61] [a]
Laboratory analysis	
Particle size distribution	Robinson pipette method [62] [b]
Total organic C (g kg^{-1})	Walkley and Black method [63]
Parameters calculated	
SOC-S (Mg ha^{-1})	SOC-S = SOC concentration × BD × d × (1–δ2mm%) × 10^{-1} [68–70] [c]
T-SOC-S (Mg ha^{-1})	T-SOC-S = Σ soil horizon $_{1\ldots n}$ SOC-S $_{\text{soil horizons}}$ [69] [d]
SOC_{sat} (g kg^{-1})	SOC_{sat} = 4.09 + 0.37 × FF [39] [e]
SOC_{def} (g kg^{-1})	$SOC_{def} = SOC_{sat}–SOC_{fine}$ [39] [f]
CO_2-eq (Mg ha^{-1})	CO_2-eq = SOC-S (Mg ha^{-1}) × (−3.67) [69,71] [g]
Clay/C ratio	SMF-clay/SOC (<20 µm); Dexter test [72] [h]

For all the parameters studied, the recommendations of the Handbook of Plant and Soil Analysis for Agricultural Systems were followed [60]. [a] 3 cm in diameter, 10 cm in length, and 70.65 cm^3 in volume. [b] Before determining particle size distribution, samples were treated with H_2O_2 (6%) to remove organic matter (OM). Particles larger than 2 mm were determined by wet sieving, and smaller particles were classified according to USDA standards [62]. [c] Where SOC is the organic carbon content (g kg^{-1}), d is the thickness of the soil layer (cm), δ2mm is the fractional percentage (%) of soil mineral particles >2 mm in size in the soil, and BD is the soil bulk density (Mg m^{-3}). [d] T-SOC-S: Total SOC stock is determined by adding all the soil horizons considered. [e] Where SOC_{sat} is the SOC saturation (g kg^{-1}) of soil fine fraction (<20 µm, clay + fine silt), and FF (%) is the fine fraction (content of soil particle size < 20 µm); SOC_{sat} = 4.09 (±1.59) + 0.37 (±0.04) × FF; numbers in parentheses refer to standard errors. [f] Where SOC_{def} is the SOC saturation deficit or SOC sequestration potential (g kg^{-1}), and SOC_{fine} is SOC in fine fraction (g kg^{-1}). [g] CO_2-eq is a term for describing different GHGs in a common unit. For any quantity and type of GHGs, CO_2-eq signifies the amount of CO_2 which would have the equivalent global warming impact. The atomic weight of a carbon atom is 12, and the atomic weight of oxygen is 16, so the total atomic weight of CO_2 is 44 (12 + (16 × 2) = 44) (44/12 = 3.67). [h] SOC/SMF: Soil organic carbon/Soil mineral fraction ratio (<20 µm).

2.4. Statistical Analyses

The effect of land management and soil depth was tested using ANOVA. Data were tested for normality to verify the model assumptions using Duncan's multiple range tests, and differences of $p < 0.05$ were considered statistically significant. All calculations were performed with Sigma Plot v14.0.

3. Results and Discussion

3.1. General Characteristics of the Studied Soils

The soils studied were CMca with vertic characteristics [53] formed from the underlying parent rock (Miocene loam and marlaceous lime) conditioned by the limestone and/or marl-limestone genesis (affected by the Ca^{2+} genesis), with little influence of the topographic position [24,73], and developed on slightly undulating slopes, well-drained, shallow (120 cm), with four differentiated horizons (Ap, Bw, BC, C) of variable thickness (Figure 3 and Supplementary Material). In this context, comparable results were obtained in CM in different Mediterranean areas for rainfed OGs, finding no significant differences ($p < 0.05$) between soil depth in the range of 119.7 cm to 128.7 cm and where the depth was limited by rock fragments [24] as in our case.

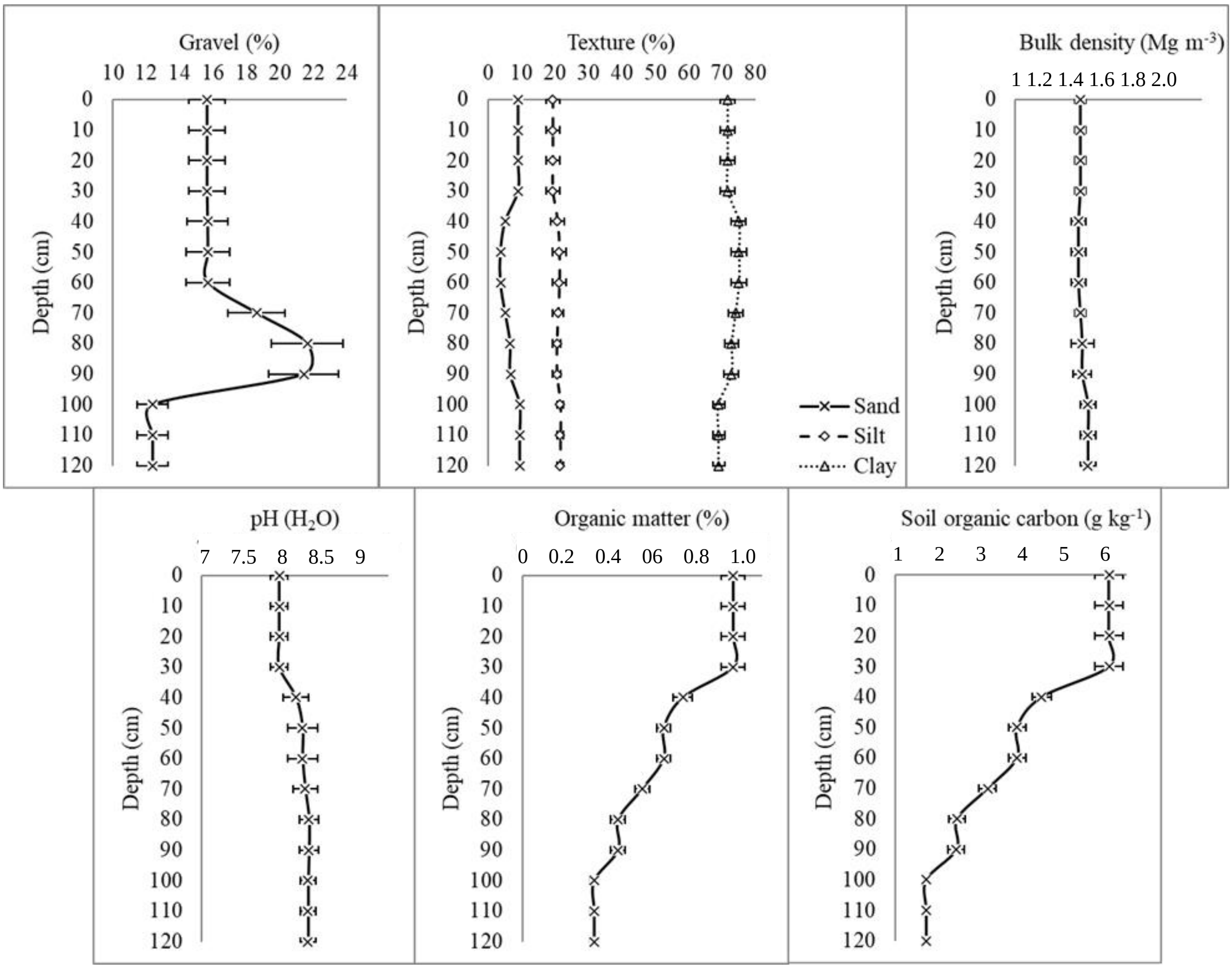

Figure 3. Physical and chemical soil properties evaluated (average ± SD) in a Mediterranean rainfed olive grove with conventional tillage—management in the study area (the end of 2018).

Texturally, they are clayey soils (Figure 3 and Supplementary Material) with high clay content, varying between 68.97% and 75.04% for the C horizon and Bw horizon, respectively. The BD increased with depth, except for the Bw horizon, which decreased slightly (Figure 3).

This unusual behavior could be due to the structure loss due to continuous tillage. This particular feature has been confirmed in the study area [27,74], so a reduction in the size of the aggregates for fractions <250 µm was found in the Bw horizon about the Ap horizon.

For the gravel content, the trend was to increase with depth, except for the C horizon, which decreased and ranged between 12.38% and 21.64% for C and BC, respectively. This performance in the gravel content at depth is unusual in CT, so the agricultural practices facilitate the gravel movement to the soil surface, increasing the surface gravel content and decreasing with depth; moreover, the water erosion promotes an increase in surface gravel content [75]. This gravel distribution along the soil profile could be due to the presence of a line of gravels and stones (BC horizon) [76] or because CT does not remove large stones at depth [77]. In many studies, the gravel content is not considered, but the gravel's presence, in addition to improving soil quality, reduces waterlogging and retards the surface runoff, increasing the infiltration rates, thus reducing runoff and sediment generation, improving water percolation, and reducing erosion processes [78]. In addition, the gravels are essential in the SOC stock (SOC-S) estimation. Accordingly, in the soil protocol, the gravel content is considered in SOC-S quantification [59,68–70,79].

The pH of the study soils was basic, varying between 7.8 and 8.2 and increasing with depth (Figure 3 and Supplementary Material). This behavior is because on hillsides under semi-arid conditions with calcareous material, the pH increases with depth due to the bedrock alteration processes [80].

3.2. Soil Mineral Fraction

The soil mineral fraction (SMF) distribution is fundamental to knowing the SOC potential storage [42], so fine SMF content affects the SOC potential storage (<20 µm) [39] since this fraction conditions the fine structural aggregate's formation (SOC + fine mineral particles), which is an essential SOC stabilization mechanism in mineral soils [37,38]. In this line, the SMF showed different behaviors depending on the size fraction (Table 2).

Table 2. Soil mineral fraction distribution in Mediterranean rainfed olive grove with CT in the entire soil profile by horizons in the study area (the end of 2018). Data are means ± SD (n = 9 × 3).

Hor.	**Depth (cm)**	**Soil Mineral Fraction—SMF %**				
		>2000 µm	2000–250 µm	250–53 µm	53–20 µm	<20 µm
Ap	0–32.7	6.66 ± 2.05 a	26.10 ± 14.67 a	47.56 ± 5.19 a	0.43 ± 0.18 a	19.23 ± 7.77 a
Bw	32.7–65.1	9.92 ± 7.50 b	44.43 ± 18.48 b	31.72 ± 7.87 b	0.31 ± 0.10 b	13.72 ± 4.28 b
BC	65.1–89.8	10.42 ± 6.65 b	32.36 ± 13.63 c	34.84 ± 4.31 b	0.36 ± 0.03 c	16.02 ± 1.37 c
C	89.8–120.0	19.91 ± 5.21 c	25.44 ± 7.14 a	37.24 ± 1.43 b	0.38 ± 0.01 c	17.03 ± 0.50 c

SD: Standard deviation; n: Replications; Hor.: Horizon; CT: Conventional tillage—centenary rainfed olive grove; Ap, Bw, BC, and C: Soil horizons. Numbers followed by different lower-case letters in the same column have significant differences ($p < 0.05$) for the same management considering different depths.

The largest mineral fraction contents were found in the ranges 2000–250 µm and 250–53 µm, while the lowest mineral fraction content was found in the 53–20 µm interval. Significant differences ($p < 0.05$) using Duncan's tests were detected regarding the fine fraction (<20 µm), and the highest concentrations were found on the soil surface (19.23%: Ap horizon), decreasing in the Bw horizon (13.72%) and, from here, increasing with depth. This increase in the fine SMF (<20 µm) in the soil surface can be associated with CT (very aggressive with the soil) [81], which accelerates microaggregate formation on the soil surface due to tillage that reduces soil porosity [82], and as a consequence, BD increases [83], as happens in the studied soils (Figure 3 and Supplementary Material), favoring crust formation and accelerating water erosion [84]. In addition, this increase in the fine soil fraction on the soil surface can also be due to the superficial horizon truncation when there are horizons rich in clay at depth so that the soil truncation occurs in the upper parts of the convex slopes due to soil erosion [85]. However, from the Bw horizon, the fine fraction content increased with depth due to the clay's superficial movement and the clay translocation throughout the soil profile [86]. Moreover, soil moisture in arid environments could increase the clay content at depth [33].

3.3. Soil Organic Carbon Distribution at Depth

The SOC and the SOC-S contents were low, ranging between 5.16 g kg^{-1} and 1.60 g kg^{-1} for the Ap and C horizons, respectively, in the SOC case, and 19.13 Mg ha^{-1} (Ap horizon) and 5.76 Mg ha^{-1} (BC horizon) for SOC-S content (Table 3); however, the total SOC-S considering the entire soil profile was 43.12 Mg ha^{-1}. Other authors have reported values of 38.9 Mg ha^{-1} for CM in CT-OG for Jaén province in the range of 0–30 cm depth [87], 30.2 Mg ha^{-1} for CM in permanent crops for Andalucía (0–25 cm) [88], and 39.9 Mg ha^{-1} for CM in OG for Spain (>100 cm depth) [89]. These differences can be due to the thickness of our soils, the references provided, and/or differences in soil management. Concerning management type, some authors [90,91] stated that Andalusia is a "high erosion risk region" with an average annual soil loss of 23.2 Mg ha^{-1}, affecting the OM, SOC, and SOC-S contents [23] and therefore producing soil decarbonization processes [92,93].

Table 3. Chemical soil properties evaluated in Mediterranean rainfed olive grove with CT in the entire soil profile by horizons in the study area (the end of 2018). Data are means ± SD (n = 9 × 3).

Hor.	pH (H_2O)	OM (%)	SOC (g kg^{-1})	SOC-S (Mg ha^{-1})	T-SOC-S (Mg ha^{-1})
Ap	7.83 ± 0.09 a	0.88 ± 0.05 a	5.16 ± 0.27 a	19.13 ± 0.24 a	43.12 ± 0.20
Bw	8.08 ± 0.16 a	0.59 ± 0.03 b	3.37 ± 0.17 b	12.36 ± 0.16 b	
BC	8.15 ± 0.10 a	0.40 ± 0.03 c	2.20 ± 0.16 b	5.76 ± 0.15 c	
C	8.14 ± 0.08 a	0.30 ± 0.02 c	1.60 ± 0.01 c	5.87 ± 0.26 c	

SD: Standard deviation; n: Replications; Hor.: Horizon; CT: Conventional tillage—centenary rainfed olive grove; OM: Organic matter; SOC: Soil organic carbon; SOC-S: Soil organic carbon stock; T-SOC-S: Total soil organic carbon stock. Numbers followed by different lower-case letters in the same column have significant differences ($p < 0.05$) considering different depths.

Comparison carried out using Duncan's tests showed significant differences ($p < 0.05$) in SOC values, decreasing with depth (Table 3 and Supplementary Material). This SOC distribution along the soil profile could be due to: (i) low rainfall and elevated temperatures (semi-arid Mediterranean conditions), (ii) the lack of crop residues in CT after drought periods, and (iii) high OM mineralization [87,94,95]. The SOC-S contents showed the same patterns as SOC, low ranges in the total SOC-S (T-SOC-S: 43.12 Mg ha^{-1}; 0–120 cm depth), and a reduction with depth (Ap: 19.13 Mg ha^{-1}, Bw: 12.36 Mg ha^{-1}, BC: 5.76 Mg ha^{-1}, and C: 5.87 Mg ha^{-1}) (Table 3). These low SOC-S contents show that OG monoculture managed by CT is unsustainable soil tillage causing soil degradation due to vegetation loss and inducing SOM impoverishment. This matter affects the soil's physical protection by promoting erosion processes and accelerating OM decomposition [96], causing SOM depletion [35] by CT (intensive tillage). In addition, the reduction in SOC and SOC-S contents with depth can also be attributed to the gravel distribution and the BD along the profile, which physically restricts roots from reaching deeper layers [97]. Furthermore, low SOC content at depth can be due to SOC stratification, as residue input is limited to the topsoil layer [95]. In this sense, the climatic conditions and clay content might affect the SOC content [98], which supports the results obtained in this study. In addition, since SOM is concentrated on the soil surface, we can deduce that C mineralization and immobilization mechanisms are more active in the soil surface layer [99].

3.4. Soil Organic Carbon Distribution by Fractions

The SOC fractionation showed that the highest SOC concentrations were in the particulate organic carbon form (POC: in the range 2000–53 µm), being 62.4%, 61.9%, 42.6%, and 44.1% for Ap, Bw, BC, and C horizons, respectively (Table 4). The SOC distribution in the SMF along the soil profile was variable, showing significant differences ($p < 0.05$) applying Duncan's tests for depth in all analyzed soil fractions and the highest SOC concentrations on the surface in the coarse POC (Ap: 10.11 g kg^{-1}; Bw: 7.71 g kg^{-1}) and for depth in mineral organic carbon (MOC) (<20 μm) with 38.1% (BC horizon: 65.1–89.8 cm depth). However, the MOC content (stable-stabilized: <20 μm) in general was high (Ap: 5.89 g kg^{-1}, Bw: 4.99 g kg^{-1}, BC: 7.38 g kg^{-1}, and C: 25.2 g kg^{-1}), with no significant differences ($p < 0.05$) in the first 65.1 cm of depth (Ap and Bw horizon).

Table 4. Soil organic carbon by fractions in Mediterranean rainfed olive grove with conventional tillage in the entire soil profile by horizons in the study area. Data are means ± SD (n = 9 × 3).

Hor.	**SOC ($g\ kg^{-1}$)**				
	>2000 [a] μm	2000–250 [b] μm	250–53 [c] μm	53–20 [d] μm	<20 [e] μm
Ap	5.80 ± 1.72 a	10.11 ± 3.39 a	9.53 ± 3.76 a	0.13 ± 0.02 a	5.89 ± 0.65 a
Bw	3.56 ± 0.97 b	7.71 ± 4.06 b	6.36 ± 0.99 b	0.11 ± 0.03 a	4.99 ± 1.26 a
BC	3.64 ± 1.74 b	3.70 ± 0.88 c	4.48 ± 1.72 c	0.17 ± 0.16 b	7.38 ± 7.11 b
C	4.35 ± 1.22 a	3.21 ± 0.32 c	3.21 ± 0.74 c	0.08 ± 0.02 c	3.65 ± 0.99 c

SD: Standard deviation; n: Replications; Hor.: Horizon; [a] >2000 μm: Heavy fraction; [b] 2000–250 μm: Particulate organic carbon—POC (coarse POC); [c] 250–53 μm: Particulate organic carbon—POC (fine POC); [d] 53–20 μm: Mineral organic carbon—associated MOC (MOC); [e] <20 μm: Mineral organic carbon—dissolved MOC (MOC). Numbers followed by different lower-case letters in the same column have significant differences ($p < 0.05$) considering different depths.

In this sense, in perennial cropping systems, the POC content is ~75% of the total C content. In other cases, MOC declines with depth ($p < 0.001$) [100]; however, POC only represents between 10% and 25% of the total C content of the soil [101]. In contrast, after reviewing more than 100 publications and data from 67 agricultural sites [102], POM is on average 21.6% of the total soil C, ranging from 1.6% to 65.1%. The results obtained in our study area about POC content are higher [100–102]. Varied factors could explain why most C was stored as POC and not MOC. In this sense, the soils studied were young soils with poor physical conditions [54] under semi-arid climatic conditions and limiting mineral erosion [103]. So, the mineral weathering provides active surfaces capable of stabilizing organic C, increasing the SOC content, and decreasing C renewal [104]. Our data corroborate this, so the studied soils were characterized by low MOC and low SMF contents in the range of <20 μm (Tables 3 and 4). In addition, in the first 65.1 cm, no significant differences ($p < 0.05$) were found in MOC (5.89 g kg^{-1}: 0–32.7 cm depth; 4.99 g kg^{-1}: 32.7–65.1 cm depth).

A critical issue is that there was no direct relationship between the SMF and MOC content in the <20 μm fraction. Therefore, not all clay particles can stabilize SOC since this depends on the mineral properties and the weathering degree [105]. However, an unexpected increase in C content (7.38 g kg^{-1}) in MOC at depth (BC: 65.1–89.8 depth) was observed, and this could be due to an extra C contribution over time and to seasonal precipitations that could saturate the soil by water, increasing mineral weathering and clay illuviation [106]. Therefore, we can say that the clay limited MOC formation, and the soil management favored POM accumulation. However, regardless of the clay content and management, an extra continuous supply of C is necessary for these soils (pruning remains, spontaneous natural vegetation, etc.), and this constant entry of C into the soil may be more important in C accumulation than the management type [107].

3.5. Critical Soil Organic Carbon Threshold—Clay/Carbon Ratio

A critical issue in the SOC context is the SOC linked to SMF (SOC/SMF ratio) since a part of SOC stabilized may be due to the physicochemical protection of OC by mineral particles [108]. Furthermore, many soil properties related to the soil's physical quality (clay dispersibility, matrix porosity, BD, etc.) are linked to the SOC/SMF-clay ratio [72]. In this sense, the threshold of 10 has been established in the clay/carbon ratio [72]. This relationship indicates that no additional SOC can be stored below 10 (SMF-clay/SOC ratio).

This threshold has been applied in several studies from different European countries with independent methodologies, and it has been determined that this threshold is critical to maintaining the soil's physical quality [72,109–111].

The approximation to the Dexter test (SMF/SOC ratio: <20 µm) [72] in the study soils indicated that this soil was susceptible to increasing the C content on the surface and at depth since the threshold in all cases was >10 (Table 5 and Supplementary Material).

Table 5. SMF/SOC (<20 µm) and SOC/SMF (<20 µm) ratios in Mediterranean rainfed olive grove with conventional tillage in the entire soil profile by horizons in the study area. Data are means ± SD (n = 9 × 3).

Hor.	**Depth (cm)**	**SMF/SOC ($g\ kg^{-1}$)**	**Δ (<20 µm) %**	**SOC/SMF ($g\ kg^{-1}$)**	**Δ (<20 µm) %**
		<20 µm	Topsoil/Subsoil	<20 µm	Topsoil/Subsoil
Ap	0–32.7	32.68 ± 9.04 a		0.0306 ± 0.0084 a	
Bw	32.7–65.1	27.47 ± 3.41 a	−15.94	0.0364 ± 0.0294 a	+18.95
BC	65.1–89.8	21.69 ± 1.93 b	−33.64	0.0461 ± 0.5190 b	+50.85
C	89.8–120.0	46.73 ± 5.05 c	+42.99	0.0214 ± 0.1980 c	−30.07

SD: Standard deviation; n: Replications; Hor.: Horizon; SOC/SMF: Soil organic carbon/Soil mineral fraction ratio; Δ (<20 µm): Increasing and decreasing in the SOC/SMF ratio in the range <20 µm. Numbers followed by different lower-case letters in the same column have significant differences ($p < 0.05$) considering different depths.

The Dexter ratio decreased significantly ($p < 0.05$) with depth up to 89.8 cm; from there, it increased, ranging from 21.69 g kg^{-1} (BC horizon) to 46.73 g kg^{-1} (C horizon). The SOC/SMF-clay relationship (Table 5) indicates that the horizon with a higher value (0.0461 g kg^{-1}) was the horizon with the least capacity to increase SOC (SMF/SOC: 21.69 g kg^{-1}: BC horizon). Similar results were found in CM in an experimental farm with crops in Padova, Italy [112], where the Dexter ratio decreased with depth, indicating that although these soils can form the SOC-clay complex, the continued tillage can reduce over time the ability to store SOC. However, we have to be careful because although the Dexter index (SMF-clay/SOC; 10) could be close to the SOC saturation concept, some authors indicate that each tillage regime should have its SOC saturation threshold [15].

3.6. Soil Organic Carbon Saturation Deficit

For the study of SOC fine (SOC_{fine}) (SOC currently <20 µm), SOC saturation (SOC_{sat}) (SOC maximum that could have <20 µm), and SOC deficit (SOC_{def}) (SOC that could accumulate <20 µm), we must start from two assumptions: (i) the primary SOC stabilization mechanism in mineral soils is the integration—the union between SOC and the finest mineral particles (<20 µm), and (ii) the amount of the fine particles in the soil is finite [39]. Therefore, the amount of stabilized SOC is conditioned by the fine particle content in the soil. One of the most accepted methods to establish the maximum SOC on the soil surface (topsoil) in the soil fine fraction (<20 µm) in tropical and temperate climates is Hassink's proposal [39] (Table 1).

The current SOC linked to the fine fraction (SOC_{fine}: <20 µm) ranged between 7.38 g kg^{-1} and 3.65 g kg^{-1}, decreasing with depth except for the BC, which increased, being 5.89, 4.99, 7.38, and 3.65 g kg^{-1} for Ap, Bw, BC, and C horizon, respectively (Figure 4 and Supplementary Material) and representing 26.0% (120 cm depth) on average of SOC_{fine}, with significant differences ($p < 0.05$) between Ap-Bw and BC and C in the SOC_{fine} content throughout the profile. Concerning the relation, "topsoil (32.7 cm)/full profile (0–120 cm depth)" was 1.18, 0.48, and 0.37 for 65.1, 89.8, and 120 cm depth, respectively.

The establishment is to consider the topsoil (surface layer) exclusively. However, minor changes in the soil surface can affect SOC at depth [98]. Therefore, when the SOC budget is analyzed, land use, management, and soil depth should be considered together [113]. In this sense, there is evidence that the C translocation to the subsoil could be produced by: (i) the vertical movement of dissolved OM, (ii) the development of deep root systems, (iii) the fauna activity, and (iv) the transport of exogenous material from the soil surface [114–117], in addition to protection against mineralization due to physical-chemical stabilization and protection biochemistry [37]. Deep plowing could increase the OC input transfer to the subsoil, improve the soil–OC mixture, and improve SOC physical protection [118]. The subsoil has a lower SOC content than the surface layer [119], suggesting that large SOC amounts could be stored at depth. In addition, in the long term, the subsoil C horizon is four times more stable than the surface layer [120], being little accessible for microorganisms and enzymes [116]. Moreover, the subsoil OC of fine root tissues, root exudates, and associated mycorrhizae is easily stabilized by physical protection mechanisms [121]. In this sense, deep-rooted crops could be a strategy to increase the stable SOC content [122]. In our case, the OG has roots that can reach up to 1.5 m depth (between 0 and 0.5 m depth: 72.7% of the roots; between 0.5 and 1.0 m depth: 22% and between 1.0 and 1.5 m: 5.3%) [123]; in addition, if there is the translocation of fresh OC, it could also contribute to increases [124] and accelerate the old SOC mineralization [115].

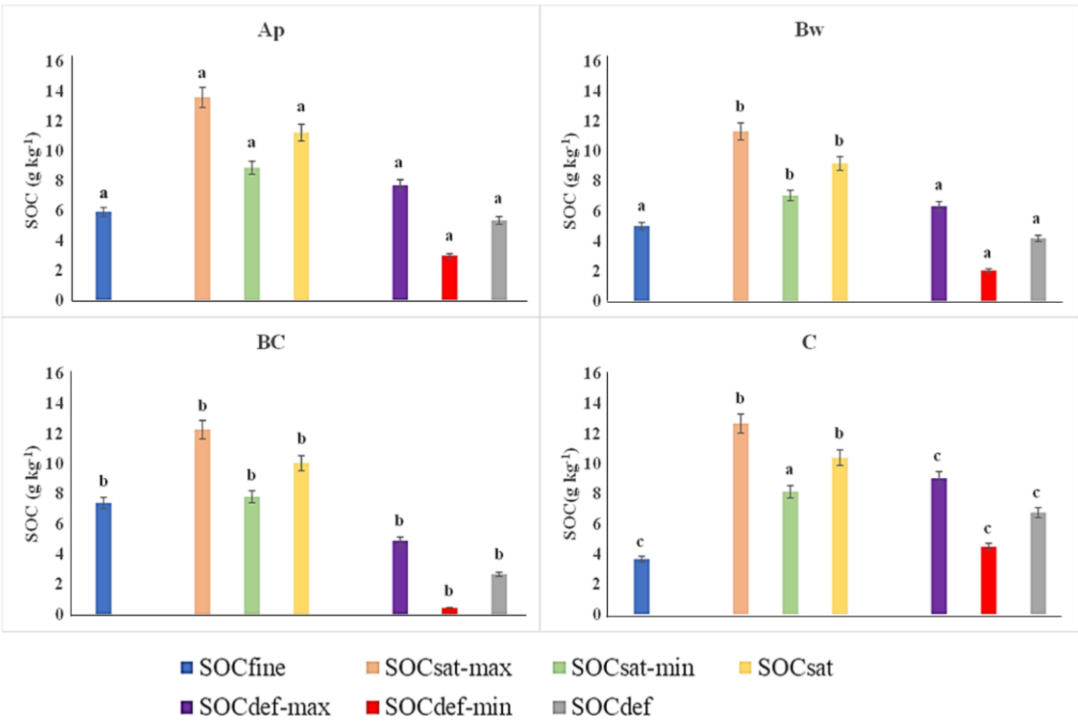

Figure 4. Soil organic carbon saturation deficit (potential sequestration) in Mediterranean rainfed olive grove with conventional tillage in the entire soil profile by horizons in the study area. Data are means ± SD (n = 9 × 3).

Horizons: Ap (0–32.7 cm), Bw (32.7–65.1 cm), BC (65.1–89.8), and C (89.8–120.0 cm). SOC_{fine}: SOC currently (<20 µm); SOC_{sat}: the SOC saturation point (<20 µm); SOC_{def}: the SOC deficit (<20 µm). $SOC_{sat} = 4.09\ (\pm 1.59) + 0.37\ (\pm 0.04) \times FF$; numbers in parentheses refer to standard errors. SOC_{sat} is the SOC saturation (g kg^{-1}) of fine soil fraction (< 20 µm, clay + fine silt) and FF (%) is the fine fraction (content of soil particle size < 20 µm). $SOC_{sat} = 5.68 + 0.41 \times FF$: Maximum SOC_{sat} value (maximum standard errors) [39]; $SOC_{sat} = 2.5 + 0.33 \times FF$: Minimum SOC_{sat} value (minimum standard errors) [39]; $SOC_{sat} = 4.09 + 0.37 \times FF$ [39]. a, b, c: Lower-case letters mean there are significant differences ($p < 0.05$) considering different depths (Ap, Bw, BC, and C) for the same property (SOC_{fine}, $SOC_{sat\text{-}max}$, $SOC_{sat\text{-}min}$, SOC_{sat}, $SOC_{def\text{-}max}$, $SOC_{def\text{-}min}$, and SOC_{def}).

For the SOC_{sat} linked to the fine fraction (Hassink's proposal for <20 µm), the values along the soil profile were homogeneous, with significant differences (Duncan's tests at $p < 0.05$) in the first 32.7 cm between topsoil (Ap) and the subsoil horizons. SOC_{sat} ranged between 11.20 g kg^{-1} (Ap) and 9.17 g kg^{-1} (Bw). As can be seen (Figure 4 and

Supplementary Material), SOC_{sat} varied as an SMF function (<20 μm), so SOC_{sat} increased when the fine fraction increased. In this line, it is essential to highlight that after applying the standard error of Hassink's approximation, SOC_{sat} increased on the surface by 21.07%, in the range of 13.56 g kg^{-1} ($SOC_{sat\text{-}max}$) to 8.84 g kg^{-1} ($SOC_{sat\text{-}min}$). Regarding deeper soil horizons, the behavior was similar to the soil surface (Figure 4 and Supplementary Material). From these data (SOC_{fine} and SOC_{sat}), we can determine that the SOC deficit (SOC_{def}) was 5.31 g kg^{-1}, 4.17 g kg^{-1}, 2.64 g kg^{-1}, and 6.74 g kg^{-1} for Ap, Bw, BC, and C horizons, respectively (Figure 4 and Supplementary Material). This means that these soils could still store, on average, 46.03% more than the current SOC_{fine} in the fine soil fraction (Ap: 47.41%; Bw: 45.47%; BC: 26.35%; and C: 64.87%) and, assuming the maximum standard error, in the Ap horizon, could store 7.67 g kg^{-1} (+56.6%) of SOC. Based on these results, we could say that carbonization–recarbonization in these soils could be possible with good management practices, and these soils are likely to increase SOC, helping mitigate climate change.

3.7. Soil Organic Carbon Sequestration Potential Density

The SOC density stock (SOC-S) in the soil fine fraction ($SOC\text{-}S_{fine}$) showed a reduction in the SOC content with depth throughout the soil profile (Ap: 21.93 Mg ha^{-1}, Bw: 18.22 Mg ha^{-1}, BC: 18.66 Mg ha^{-1}, and C: 13.55 Mg ha^{-1}), with no significant differences ($p < 0.05$) in the first 86 cm and without a direct relationship with the fine SMF (Table 2, Figure 5, and Supplementary Material). The T-SOC-S density in the $SOC\text{-}S_{fine}$ in the entire soil profile was 72.36 Mg ha^{-1}. It is important to underscore the high SOC-S density at depth (50.43 Mg ha^{-1}: Bw+BC+C) compared to SOC-S on the surface (21.93 Mg ha^{-1}: Ap). Therefore, at depth (>32.7 cm), the $SOC\text{-}S_{fine}$ represents 69.62% of the T-SOC-S of the soil fine fraction; this indicates that the SOC below the arable layer contributes significantly to the total C reserves. In this line, different research teams [98,125] have found in the "topsoil/full profile" relation in croplands values of 0.48 and ranges between 0.56 and 0.26. In our study area, this relationship is 0.37 and 0.30 for a depth of 89.9 cm and 120 cm, respectively. This high SOC-S concentration at depth may be due to leaching in soils with traditional management-disturbed soils [126] because the plow redistributes the SOC at depth and because the OG roots are deep [123].

Concerning the $SOC\text{-}S_{sat}$, it decreased with depth, except for the C horizon which increased, highlighting high $SOC\text{-}S_{sat}$ in Ap (41.90 Mg ha^{-1}) and C (38.23 Mg ha^{-1}), with low values in BC (26.27 Mg ha^{-1}), therefore conditioning the $SOC\text{-}S_{def}$, with a $T\text{-}SOC\text{-}S_{sat}$ of 140.19 Mg ha^{-1}, and ranging from 171.05 Mg ha^{-1} ($T\text{-}SOC\text{-}S_{sat\text{-}max}$) to 109.33 Mg ha^{-1} ($T\text{-}SOC\text{-}S_{sat\text{-}min}$) according to maximum and minimum standard errors of the Hassink approximation (Figure 5 and Supplementary Material). The $SOC\text{-}S_{def}$ was 19.97, 15.58, 7.61, and 24.68 Mg ha^{-1} for Ap, Bw, BC, and C, respectively, with a $T\text{-}SOC\text{-}S_{def}$ in the entire soil profile (120 cm) of 67.84 Mg ha^{-1} linked exclusively to fine SMF. These results indicate that: (i) in topsoil (Ap horizon: 32.7 cm depth), these soils could store between 28.76 Mg ha^{-1} and 11.17 Mg ha^{-1} more $SOC\text{-}S_{fine}$ in the SMF (<20 μm), and (ii) considering the entire soil profile, these soils could store between 98.69 and 36.97 Mg ha^{-1} more $SOC\text{-}S_{fine}$ in the SMF (<20 μm) (Figure 5 and Supplementary Material), taking into account in both cases the maximum and minimum standard errors of the Hassink approximation [39].

Horizons: Ap (0–32.7 cm), Bw (32.7–65.1 cm), BC (65.1–89.8), and C (89.8–120.0 cm). SOC_{fine}: SOC currently (<20 μm); SOC_{sat}: the SOC saturation point (<20 μm); SOC_{def}: the SOC deficit (<20 μm). $SOC_{sat} = 4.09\ (\pm 1.59) + 0.37\ (\pm 0.04) \times FF$; numbers in parentheses refer to standard errors. SOCsat is the SOC saturation (g kg^{-1}) of fine soil fraction (<20 μm, clay + fine silt), and FF (%) is the fine fraction (content of soil particle size < 20 μm). $SOC_{sat} = 5.68 + 0.41 \times FF$: Maximum SOC_{sat} value (maximum standard errors) [39]; $SOC_{sat} = 2.5 + 0.33 \times FF$: Minimum SOC_{sat} value (minimum standard errors) [39]; $SOC_{sat} = 4.09 + 0.37 \times FF$ [39]. a, b, c: Lower-case letters mean there are significant differences ($p < 0.05$) considering different depths (Ap, Bw, BC, and C) for the same property (SOC_{fine}, $SOC_{sat\text{-}max}$, $SOC_{sat\text{-}min}$, SOC_{sat}, $SOC_{def\text{-}max}$, $SOC_{def\text{-}min}$, and SOC_{def}).

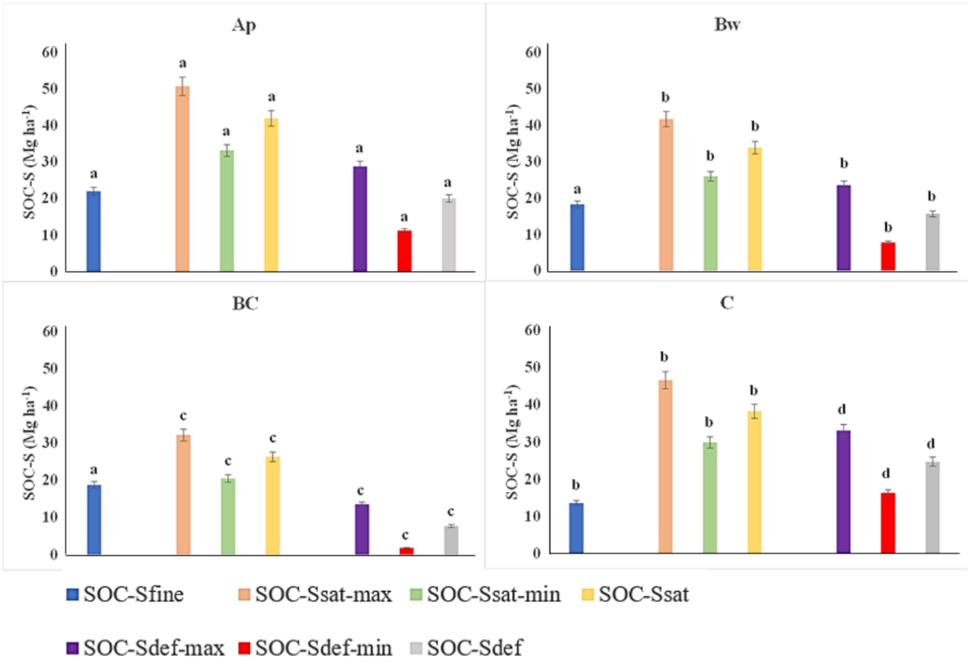

Figure 5. Soil organic carbon density saturation deficit (potential sequestration) in Mediterranean rainfed olive grove with conventional tillage in the entire soil profile by horizons in the study area. Data are means ± SD (n = 9×3).

3.8. CO_2-Equivalent in the Study Soils

For the study of CO_2-eq, we started with technical feasibility (current SOC-S and SOC sequestration potential), considering the Recarbonizing Global Soils program indications [127] as a part of the Recarbonization of Global soils strategy (RECSOIL) [128], to later (in the coming years) implement SSM and, in this way, to be able to increase SOC-S to offset GHG.

The soils of the study area store actually in the form of SOC-S_{fine} (<20 µm) 80.48 Mg ha^{-1} of CO_2-eq on the surface (0–32.7 cm) and 185.08 Mg ha^{-1} of CO_2-eq at depth (32.7–120 cm), respectively (Figure 6 and Supplementary Material).

The average capacity to store CO_2-eq from the C saturation estimation [39] is 153 Mg ha^{-1} of CO_2-eq on the surface (0–32.7 cm) and 360.32 Mg ha^{-1} of CO_2-eq at depth (32.7–120 cm), respectively. However, if we take into account the standard errors of the Hassink determination [39], in topsoil (0–32.7 cm), they could store between 186.03 Mg ha^{-1} of CO_2-eq and 121.51 Mg ha^{-1} of CO_2-eq, while at depth (32.7–120 cm), they could store between 438.05 Mg ha^{-1} of CO_2-eq and 279.73 Mg ha^{-1} of CO_2-eq. From these data, we can deduce that these soils, on average, have a net C sink capacity of 73.29 Mg ha^{-1} of CO_2-eq on the surface and 175.69 Mg ha^{-1} of CO_2-eq at depth and oscillate between 105.55 and 41.00 Mg ha^{-1} of CO_2-eq at surface and between 256.64 and 94.69 Mg ha^{-1} of CO_2-eq at depth. These results indicate that these soils have an extremely high capacity to be C sinks. In this sense, the RECSOIL strategy [128] suggests that for soils with a high capacity for C sink, the objective should be SSM implementation, constituting a feasible solution to offset global emissions. In addition, the EU Soil Strategy for 2030 (Reaping the benefits of healthy soils for people, food, nature, and climate) [129] in its medium-term objectives by 2030 highlights: (i) significant areas of degraded and carbon-rich ecosystems, including soils, will be restored (EU Biodiversity Strategy for 2030, COM-2020–380), and (ii) achieve an EU net greenhouse gas removal of 310 million Mg CO_2-eq per year for the land-use, land-use change, and forestry sector (Proposal for a revision of the LULUCF Regulation, COM-2021-554).

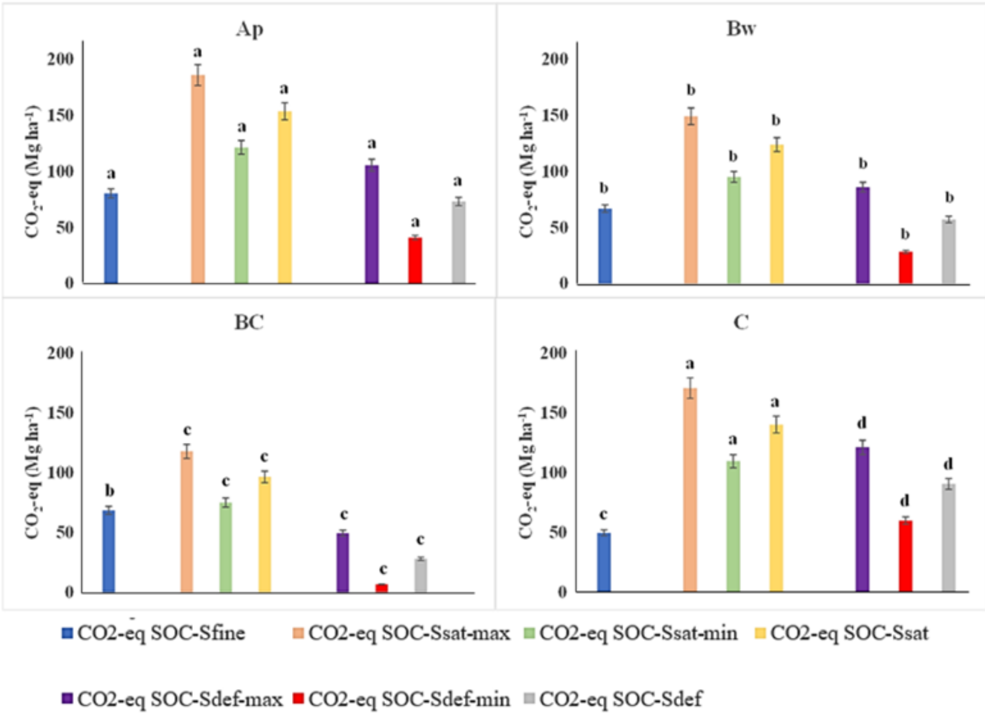

Figure 6. CO_2-eq in Mediterranean rainfed olive grove with conventional tillage in the entire soil profile by horizons in the study area. Data are means ± SD (n = 9×3).

Horizons: Ap (0–32.7 cm), Bw(32.7–65.1 cm), BC (65.1–89.8), and C (89.8–120.0 cm). a, b, c: Lower-case letters mean there are significant differences ($p < 0.05$) considering different depths (Ap, Bw, BC, and C) for the same property (CO_2-eq-SOC-S_{fine}, CO_2-eq-SOC-$S_{sat\text{-}max}$, CO_2-eq-SOC-$S_{sat\text{-}min}$, CO_2-eq-SOC-S_{sat}, CO_2-eq-SOC-$S_{def\text{-}max}$, CO_2-eq-SOC-$S_{def\text{-}min}$, and CO_2-eq-SOC-S_{def}).

4. Conclusions

These soil data are the starting point of the Diverfarming project (EU Horizon 2020) about the OG susceptibility to being carbon sinks (by soil recarbonization), implementing sustainable soil management (the following years) according to the RECSOIL strategy (FAO, 2019) and the EU Soil Strategy for 2030 (EU, 2021).

Similar to many Mediterranean OGs, the studied soils were degraded due to management (strongly mechanized over time), characterized by low SOC content (5.16 g kg^{-1}) and low SOC-S (19.13 Mg ha^{-1}) in topsoil due to soil tillage, Mediterranean semi-arid conditions, the lack of crop residues in conventional tillage after drought periods, and the high OM mineralization rate.

Concerning SOC, the highest SOC concentrations were located in POC (62.4% in topsoil). These high POC contents may be due to the studied soils being young soils in a semi-arid climate and with limited mineral erosion, and these conditions do not favor SOC stabilization.

The use of two indicators (Dexter test—clay/carbon ratio: qualitative analysis and Hassink approximation—SOC-Ssat: quantitative analysis) indicated that these soils have a high capacity for SOC storage. The Dexter test (ranging from 21.69 to 46.73) showed that these soils have a potential capacity to store C (two or three times more C than the current C). However, the Hassink approximation indicated that the C stabilized (SOC_{fine}) on the surface was 5.89 g kg^{-1} (21.93 Mg ha^{-1}), being able to store (SOC_{sat}) 11.20 g kg^{-1} (41.90 Mg ha^{-1}), and with a C deficit (SOC_{def}) of 5.31 g kg^{-1} (19.97 Mg ha^{-1}) being able to store up to 28.76 Mg ha^{-1} on the surface if we assume the standard errors of Hassink approximation.

Extrapolating these results to CO_2-eq on the soil surface, we can indicate that these soils could store 153.77 Mg CO_2-eq ha^{-1}, reaching up to 186.03 Mg CO_2-eq ha^{-1}, with a deficit maximum of 105.55 Mg CO_2-eq ha^{-1}. However, if we consider the soil's entire profile, these soils will have an average deficit of 248.98 Mg CO_2-eq ha^{-1} and a maximum deficit of 362.19 Mg CO_2-eq ha^{-1}. Therefore, intervening in these soils and applying good management practices could be an essential source of C natural sinks.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142114609/s1.

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