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What Influence Does Conventional Tillage Have on the Ability of Soils to Sequester Carbon, Stabilise It and Become Saturated in the Medium Term? A Case Study in a Traditional Rainfed Olive Grove

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Abstract: Soils have the capacity to store three times more carbon (C) than the atmosphere. This fact has focused scientific and governmental attention because it is one way to mitigate climate change. However, there comes a time when the capacity of soils to store C reaches a limit, considering soil organic carbon (SOC) saturation. In the Mediterranean area, agricultural soils are traditionally exposed to conventional tillage (CT), causing soil properties and quality degradation. Therefore, this study aimed to determine whether CT modifies the carbon storage capacity (carbon saturation), linked to soil mineral fractions <20 μm in olive grove soil in a Mediterranean area over 15 years. The results showed losses of SOC and soil organic carbon stock (SOC-S) over the period studied. Moreover, CT significantly affected aggregate grain size, reducing the percentage of small macro-aggregates (2000–250 μm) by 51.1%, 32.9%, 46.6%, and 50.6% for the Ap, Bw, BC, and C horizons, respectively, and promoting an increase in fine fractions (large micro-aggregates (250–53 μm), silt + clay fraction (53–20 μm) and fine silt + clay (<20 μm)). After 15 years, SOC fractionation showed a decrease in SOC concentration within the large macro-aggregate fraction (>2000 μm) of 38.6% in the Bw horizon; however, in the small macro-aggregates (2000–250 μm), an increase in SOC concentration over time, of 33.5%, was observed in the Ap and Bw horizons. This increasing trend continued in the fine soil fractions. Concerning SOC bound to the fine mineral fraction (<20 μm), evolution over time with CT led to an increase in soil sequestration capacity in the first horizons of 44.7% (Ap horizon) and 42.9% (Bw horizon), and a decrease in depth (BC horizon) of 31.3%. Finally, the total saturated soil organic carbon stock (T-SOC-S_{sat}), after 15 years, experienced an increase of 30.5 Mg ha^{-1}, and these results conditioned the soil organic carbon stock deficit (SOC-S_{def}), causing a potential increase in the capacity of soils to sequester carbon, of 15.2 Mg ha^{-1} in 15 years. With these results, we can affirm that the effect of CT in the medium term has conditioned the degradation of these soils and the low SOC concentrations, and has therefore made it possible for these soils, with the application of sustainable management practices, to have a high carbon storage capacity and become carbon sinks.

Keywords: soil degradation; particle size distribution; soil C saturation; climate change; land management; soil mineral fraction

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1. Introduction

As a consequence of human activities and as shown by the latest studies, humanity is facing climate change (CC) as one of its most significant problems on a global scale. The main reason is the modification in the composition of the atmosphere by the increase in anthropogenic greenhouse gases (GHGs) (CO_2, CH_4, N_2O, and HFCs, among others) [1–3].

In this context, carbon (C) is a chemical element present in organic compounds [4], which circulates between different reservoirs (oceanic, atmospheric, biotic, and pedological), with strong C exchanges occurring between the terrestrial and atmospheric reservoirs in response to natural processes, such as photosynthesis, soil respiration, and erosion processes, in addition to anthropogenic gas emissions [5].

It is essential to know and understand these mechanisms and interactions to control changes in soil C content, as it can store C for thousands of years until it becomes saturated [6]. Therefore, soil can play a crucial role in CC mitigation [7]. In general, soil has the capacity to store three times more C than the atmosphere, and soils contain 71% of the terrestrial Organic Carbon (OC) pool [8–10].

But this capacity of soil to store C, to be a C sink, is not finite and has a limit [11], that is, the soil reaches a point where it can no longer store more C and becomes saturated. Thus, when we talk about soil organic carbon (SOC) saturation, we refer to the maximum capacity of soil to store SOC [12].

In this regard, it has been demonstrated that the formation of organic-mineral complexes in the fine soil fractions (fine silt and clay: <20 µm) is the essential process for stabilising SOC [13,14]. To estimate the capacity of fine particles to stabilise C in soils, [11] used a linear least squares regression between the SOC associated with the fine soil fraction and the relative mass of this fraction. Subsequent publications have highlighted the influence of clay type and land use on the calculation of soil saturation [15–17]. As the notion of SOC saturation is attributed to the soil's fine fraction, the soil's sequestration potential can be calculated as the difference between the theoretical SOC saturation and the SOC stored in the fine fraction.

However, the inherent capacity of soils to stabilise SOC is related to the medium term (more than 15–20 years) and the fine fraction, so the concept of saturation deficit may not be suitable for estimating short or medium term (<15 years) SOC storage potential [12].

Focusing on Mediterranean soils, and therefore on Spanish soils, they have the opportunity to become a soil C sink because they are characterized by a low OM content (~1%) due to climatic conditions, low C addition from plant residues, low plant density, and above all, the intense tillage (conventional management) that has dominated over time in these areas [18,19]. Therefore, by reducing tillage and acting on the vegetation cover, soil recarbonization could be achieved [20–23], according to the recommendations of the Recarbonizing Global Soils program [24] as a part of the RECSOIL (Recarbonization of Global soils) strategy [25] in order to be able to subsequently implement sustainable soil management and increase the SOC stocks and thus offset GHGs, in addition to improving food security and farmers' income, providing ecosystem services, and contributing to the achievement of the Sustainable Development Goals.

In the agricultural areas under Mediterranean climatic conditions, olive groves are primarily used, with more than 5 Mha [26]; and Spain is the country with the highest olive oil production in the world, with a net production of 47% worldwide [27]. However, this development of olive orchards in Mediterranean areas has negative consequences for the soil, as a low OM content characterizes olive orchard soils (<2%) [28] and, therefore, it would be necessary to act on them to increase the OM content of the soil (SOM) [29]. It is equally important to know the maximum carbon sequestration capacity in order to establish soil capacity in olive orchards to act as a carbon sink, mitigating CC.

Soil management with conventional tillage (CT) is a traditional and common management practice in olive orchards and has been widely adopted over time because it is associated with several environmental benefits (improved water infiltration, removal of weeds, plugging cracks in the soil, etc.). However, CT is one of the main causes of the decrease in SOM, aggregate stability, and root breakage, and it also favours SOM mineralization. The physical protection of the aggregates and the stability of SOC can be altered by CT, shortening the life cycle of the macro-aggregates, making them unstable and subsequently destroyed, thus causing a decrease in the formation of new micro-aggregates and reducing the capture of C within them [30].

In this sense, this study aimed to determine whether CT tillage modifies the capacity to store carbon (carbon saturation) in olive grove soils in Mediterranean areas over 15 years (medium term). To achieve this goal, the SOC associated with the soil mineral fractions considering all depths was determined in the medium term (15 years), focusing on the fraction <20 µm to quantify the SOC saturation and the deficit.

2. Materials and Methods

2.1. Characterization of the Study Area

The study site is located on an experimental farm of a centenary rainfed olive grove (*Olea europea* var. Picual) in Garcíez-Torredelcampo in the province of Jaén (Spain), with traditional management (37°50′ N–3°52′ W: 441 m.a.s.l.) and a slope varying from 0% to 8% (Figure 1). Here, soil parent materials are Miocene marls and marl-limestones, and the predominant soils are calcaric Cambisols with some vertic characteristics, according to the World Reference Base for Soil Resources [31]. The main characteristics of the study area are described in Table 1.

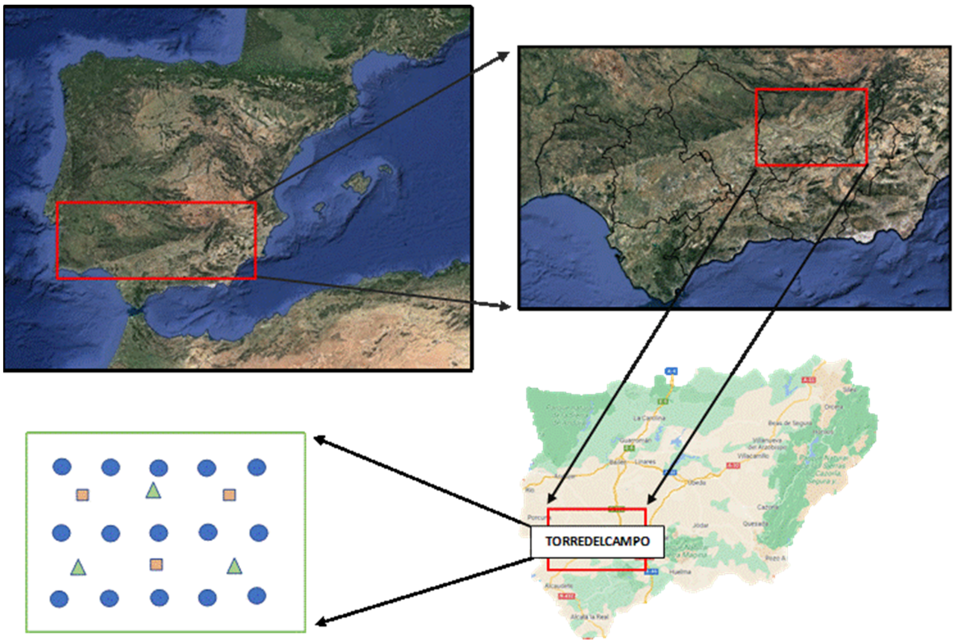

Figure 1. Location of the study area. Garcíez-Torredelcampo (Jaén-Spain)—(37°50′20′′ N–3°52′32′′ W). The blue circles represent olive trees, the orange squares represent profiles excavated in 2003, and the green triangles represent profiles excavated in 2018.

Table 1. Main characteristics of the study area.

Parameter	Description		References
Climate	Mediterranean		[32]
Climatic characteristics	Average annual rainfall	485.92 mm	[33]
	Average annual temperature	16.7 °C	
	Maximum temperature of the period	45.8 °C	
	Minimum temperature of the period	−9.6 °C	
	Relative humidity	60.8%	
	Average annual reference evapotranspiration (ETo)	1330.2 mm	
Soil type	Calcaric Cambisols		[31]
Soil properties	Clayey texture	Basic pH	[34]
Soil characteristics	Low fertility	Physical conditions not optimal	[27]

2.2. Experimental Design

The experimental design studied soil C storage capacity (saturation) in traditional rainfed olive groves of the Picual variety with CT. The CT was characterized in the following manner. Once the olives were harvested, mineral fertilization was applied (100 kg ha^{-1} of urea (46% N) in alternate years). Subsequently, every two years, the olive trees were pruned, and shredded pruning residues (6 Mg ha^{-1}) were added to the soil. After this, a disc harrow (25 cm) was used, and then a cultivator pass to reduce the size of the clods in summer, and finally, herbicide was added to control weeds in autumn (the last two practices were applied only under the trees) (Figure 2).

Figure 2. Conventional management experimental plot.

Soil properties were studied at different depths within the soil profile, horizon by horizon, and under the same topographic orientation.

2.3. Sample Preparation and Physico-Chemical Analysis

Three complete soil profiles were selected both in 2003 and 2018. Soil samples were collected along the different soil horizons for each soil profile, thus avoiding mixing pedogenetic horizons and determining adequate soil physical and chemical properties. Three laboratory replicates were performed, obtaining a total of nine replicates (3 soil profiles × 3 laboratory replicates = 9) for each horizon in the two sampling years, both in CT0 = 2003 and CT1 = 2018.

Soil samples were placed in labeled polythene bags, transferred to the laboratory, and air-dried. Once dried, the samples were sieved through an 8 mm sieve to remove rock and root debris for the subsequent wet sieving procedure. Another part of the samples was sieved with a 2 mm sieve, separating the coarse fragments from the rest of the material for the rest of the analysis.

According to the Handbook of Plant and Soil Analysis for Agricultural Systems, the analytical methods, laboratory analyses, and other calculated parameters used to determine the different soil properties were carried out [35].

Based on the wet sieving method of [36], soil size fractionation into four fractions, firstly (>2000 μm, 2000–250 μm, 250–53 μm, and 53–20 μm) described in the work of [34], was performed. Secondly, the <20 µm fraction was obtained according to the method described in works such as [37,38].

Bulk density (Mg m^{-3}) was measured in the field using the cylinder method [39], with a cylinder of 3 cm diameter, 10 cm depth, and a total volume of 70.65 cm^3.

The particle size distribution (soil texture) was analysed using the Bouyoucos hydrometer method [40]. Before determining the particle size distribution, the samples were treated with H_2O_2 (6%) in order to remove OM.

SOC was calculated using the Walkley and Black method [40]. With regard to the calculated parameters, they were determined in the following manner.

Soil organic carbon stock (SOC-S) in Mg ha^{-1} was obtained by Equation (1).

$$\text{SOC-S} = \text{SOC concentration} \times \text{BD} \times \text{d} \times (1 - \delta 2\ \text{mm\%}) \times 10^{-1} \quad (1)$$

where SOC is the organic carbon content in g kg^{-1}, d is the horizon thickness (cm), δ2 mm is the percentage of the mineral fraction greater than 2 mm, and BD is the bulk density in Mg m^{-3} [1,41]. The total soil organic carbon stock (T-SOC-S), in Mg ha^{-1}, was obtained by Equation (2).

$$\text{T-SOC-S} = \Sigma_{\text{soil horizon } 1 \ldots n}\ \text{SOC-S}_{\text{soil horizons}} \quad (2)$$

where T-SOC-S is obtained by summing all corresponding soil horizons [1].

The soil organic carbon saturated SOC_{sat}, in g kg^{-1}, was obtained by Equation (3).

$$SOC_{sat} = 4.09 + 0.37 \times FF \quad (3)$$

where SOC_{sat} is the SOC saturation (g kg^{-1}) of soil fine fraction (<20 µm, clay and 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 [11].

The soil organic carbon deficit SOC_{def}, in g kg^{-1}, was obtained by Equation (4).

$$SOC_{def} = SOC_{sat} - SOC_{fine} \quad (4)$$

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}) [11].

2.4. Statistical Analyses

For the statistical analysis, the effect of land management on aggregate size distribution, SOC associated with aggregates, SOC associated with <20 µm fraction, and saturated and deficit SOC and SOC-S were analysed using a normality test of the data to verify model assumptions using the Kolmogorov–Smirnov test. As it was observed that the data failed the normality test, non-parametric tests (Kruskal–Wallis ANOVA) were used. Significant differences between different time periods with the same treatment and along the soil profile were determined by one-way analysis of variance, followed by significant difference using Tukey's test at $p < 0.05$. All calculations were performed with Sigma Plot v14.0.

3. Results and Discussion

3.1. Main Characteristics of the Soils Studied

The soils in the study area were calcaric Cambisols with some vertic characteristics according to the IUSS Working Group WRB [31]. They were characterized by a low gravel content, clayey texture, basic pH, and low organic matter content [27]. It should be noted that this soil type did not derive from their physiographic position, but they were formed from the parent rock, and their calcareous properties conditioned their formation. They were young soils developed on slightly undulating slopes, with good drainage, with a sequence of Ap-Bw-C horizons, and characterized by low fertility, poor physical conditions, and a regular capacity for agricultural use [32].

The soils studied had a thickness up to 120 cm in depth (Table 1), with slight variations in slope length, slope, and topographic position of the study area [27].

Another important property of these soils was the gravel content, with low values, ranging from 12.6% on the C-2003 horizon to 21.6% on the BC-2018 horizon (Table 2), and no significant differences ($p < 0.05$) over time. In general, the trend was an increase in the gravel content at depth until the BC horizon, and then the gravel content decreased at the C horizon. This behaviour may be interpreted in different ways, such as CT not removing large stones at depth (C horizon) [42], the presence of a line of gravels and/or stones in the C horizon due to the depth of ploughing, as postulated by [43], or a combination of both interpretations.

Table 2. Soil physical properties assessed by horizons (average ± SD) in Mediterranean olive orchard with conventional tillage in 2003 (CT0) and in 2018 (CT1) ($n = 3 \times 3$).

Land Management	Ch.	Hor.	Th (cm)	Depth (cm)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	BD (Mg m^{-3})
CT0	CM-ca $n = 9$ 2003	Ap	27.4 ± 1.1	0–27.3	12.6 ± 1.2 Aa	8.6 ± 1.0 Aa	19.5 ± 2.6 Aa	71.9 ± 3.6 Aa	1.42 ± 0.17 Aa
		Bw	28.3 ± 1.1	27.3–55.6	13.5 ± 1.3 Aa	5.5 ± 1.3 Ba	22.7 ± 3.1 Aa	71.8 ± 4.4 Aa	1.43 ± 0.09 Aa
		BC	33.2 ± 1.1	55.6–88.8	17.6 ± 1.4 Ba	3.8 ± 0.7 Ca	24.7 ± 3.2 Aa	71.7 ± 3.9 Aa	1.44 ± 0.05 Aa
		C	26.4 ± 1.0	88.8–115.2	12.6 ± 0.8 Aa	4.5 ± 1.0 Ca	21.8 ± 1.9 Aa	73.7 ± 2.9 Aa	1.44 ± 0.10 Aa
CT1	CM-ca $n = 9$ 2018	Ap	32.7 ± 1.2	0–32.7	15.6 ± 1.1 Aa	9.0 ± 0.3 Aa	19.3 ± 2.0 Aa	71.7 ± 2.2 Aa	1.35 ± 0.03 Aa
		Bw	32.4 ± 0.8	32.7–65.1	15.7 ± 1.3 Aa	3.7 ± 0.2 Ba	21.3 ± 2.1 Aa	75.0 ± 2.3 Ba	1.34 ± 0.04 Aa
		BC	24.6 ± 1.0	65.1–89.8	21.6 ± 2.1 Ba	6.6 ± 0.9 Ba	20.5 ± 1.2 Ab	72.9 ± 2.1 Aa	1.36 ± 0.06 Aa
		C	30.2 ± 0.9	89.8–120.0	12.4 ± 0.9 Aa	9.5 ± 0.9 Ab	21.5 ± 0.9 Aa	69.0 ± 1.8 Ab	1.39 ± 0.04 Ba

CT0 (2003) and CT1 (2018): Conventional tillage-centenary rainfed olive grove; SD: Standard deviation; Ch: Characteristics; Hor.: Horizon; Th: Thickness; BD: Bulk density; Texture (USDA, 2004). CM-ca: Calcaric Cambisols (IUSS Working Group WRB, 2015); n = Sample size. Numbers followed by different capital letters within the same column have significant differences ($p < 0.05$) between depths considering the same land management. Numbers followed by different lower-case letters within the same column have significant differences ($p < 0.05$) between the same soil horizon and the same land management considering different periods of time.

The soils were texturally clayey, with few differences in silt and clay content at depth. (Table 2). It is important to highlight that this particle distribution reduces infiltration rates, increases surface runoff, and increases sediment concentrations and erosion rates, worsening water percolation and increasing erosion by slowing erodibility and runoff [44], which are critical processes when the topography is not flat (undulating slopes, as is the case in the study area). In addition to these processes, there must be added, on the one hand, the effect of the intense CT carried out on the study soils, which causes the elimination of the vegetation cover of the soil and therefore the decrease in OM in the soil, and on the other hand, the climatic characteristics of the area, with low rainfall and high temperatures.

Regarding bulk density (BD) for the two situations (2003–2018), it showed slight increases in depth (Table 2) with no significant differences ($p < 0.05$). The trend was a slight reduction in BD in 2018 compared to 2003, which may have been due to a loss of soil organic matter (SOM). These results demonstrate that the change in soil aggregate size that occurred over time due to CT (reducing coarse fractions and increasing fine fractions) could reduce soil density. Regarding this statement, [45] indicates that CT produces a mechanical breakdown of aggregates, reducing soil macro-aggregates, and favouring the formation of micro-aggregates together with a loss of SOM.

pH tended to increase at depth, with no significant differences ($p < 0.05$) observed in CT over 15 years (2003–2018) (Table 3). It is essential to highlight that, according to authors such as [46], soil pH is conditioned by climate, topography, and lithology, that is, pH should increase in depth due to the processes of alteration of the parent rock on slopes with calcareous lithology and semi-arid conditions such as those found in our study area.

Table 3. Soil chemical properties assessed by horizons (average ± SD) in Mediterranean olive orchard with conventional tillage in 2003 (CT0) and in 2018 (CT1) ($n = 3 \times 3$).

Land Management	Hor	pH (H_2O)	OM (%)	SOC (g kg^{-1})	SOC-S (Mg ha^{-1})	T-SOC-S (Mg ha^{-1})
CT0	Ap	7.63 ± 0.26 Aa	1.25 ± 0.06 Aa	7.3 ± 0.38 Aa	24.7 ± 2.5 Aa	74.74 ± 1.5
	Bw	8.08 ± 0.23 Aa	1.01 ± 0.04 Aa	5.8 ± 0.23 Aa	20.2 ± 2.5 Aa	
	BC	8.19 ± 0.16 Aa	0.78 ± 0.05 Ba	4.3 ± 0.26 Aa	17.0 ± 0.5 Ba	
	C	8.11 ± 0.19 Aa	0.74 ± 0.06 Ba	3.9 ± 0.29 Ba	12.9 ± 0.4 Ba	
CT1	Ap	7.83 ± 0.09 Aa	0.88 ± 0.05 Ab	5.2 ± 0.27 Aa	19.1 ± 0.20 Aa	43.12 ± 0.20
	Bw	8.08 ± 0.16 Aa	0.59 ± 0.03 Bb	3.4 ± 0.17 Bb	12.4 ± 0.16 Ba	
	BC	8.15 ± 0.10 Aa	0.40 ± 0.03 Cb	2.2 ± 0.16 Ba	5.8 ± 0.15 Cb	
	C	8.14 ± 0.08 Aa	0.30 ± 0.02 Cb	1.6 ± 0.01 Ca	5.9 ± 0.26 Cb	

CT0 (2003) and CT1 (2018): Conventional tillage-centenary rainfed olive grove; SD: Standard deviation; Hor.: Horizon; n = Sample size; 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 capital letters within the same column have significant differences ($p < 0.05$) between depths considering the same land management. Numbers followed by different lower-case letters within the same column have significant differences ($p < 0.05$) between the same soil horizon and the same land management considering different periods of time.

Regarding the soil's chemical properties, a critical issue was to analyze the concentrations of SOM, which were generally very low, tending to decrease in depth and ranging between 0.30% in the C-2018 horizon and 1.25% in the Ap-2003 horizon, with a decrease in concentrations in the period 2003–2018, with CT (Table 3).

CT in the continuous cultivation of rainfed olive groves causes the loss of SOM due to the lack of plant debris and a low contribution in these agronomic conditions, favoured by the periodic physical disturbance of the soil due to the mechanical labours [47–49]. However, in contrast to this management, [50], in their study in olive orchards under cover crop management systems for three years (bare soil, olive orchard intercropped with *Canavalia ensiformis* and spontaneous vegetation, olive orchard in rotation with *Pennisetum glaucum*, *Crotalaria juncea* and spontaneous vegetation, and olive orchard with cleared spontaneous vegetation), show how the decrease in tillage and the presence of vegetation leads to an increase in both SOM and soil quality.

In both cases (2003 and 2018), SOC content tends to vary within the soil profile, decreasing at depth, varying between 7.3 g kg^{-1} and 3.9 g kg^{-1} (2003) and 5.2 g kg^{-1} and 1.6 g kg^{-1} (2018) in the Ap and C horizons, respectively (Table 3), besides the observed losses in SOC through the period studied. In Mediterranean olive groves managed under CT, authors such as [51,52] have obtained similar results in their studies, showing that this tendency of SOC reduction at depth may be due to, firstly, the semi-arid Mediterranean conditions (low rainfall and high temperatures), secondly, the lack of crop residues in CT after periods of drought, and thirdly, the high mineralization of SOM.

Regarding SOC stock (SOC-S), it followed the same trend as SOC, decreasing both in depth and overtime in 2003 and 2018, with values between 24.7 Mg ha^{-1} and 12.9 Mg ha^{-1} (2003) and 19.1 Mg ha^{-1} and 5.9 Mg ha^{-1} (2018) for the Ap and C horizons, respectively (Table 3). This heterogeneity in SOC-S distribution is because the C stock depends on gravel content, BD, SOC, and horizon thickness [1,41,53]. Furthermore, SOC-S decreased over the period studied, from 74.7 Mg ha^{-1} to 43.1 Mg ha^{-1}, causing clear decarbonisation of the soil in this period (15 years). This implies that CT caused soil degradation processes due to the absence of vegetation and unsustainable soil management, leading to an impoverishment of SOM content. This affects the physical protection of the soil, favoring erosion processes and accelerating the rate of SOM decomposition by CT [54,55]. However, although it is well established that sustainable management practices, including reduced tillage, lead to an increase in C values over time [56], authors such as [57] have observed the decrease of SOC-S in agricultural soils in the long term when reduced or no-tillage (NT) practices were applied on cropland. Therefore, continuous tillage, maintenance of bare soils, and high erosion rates have been identified among the main factors for the decrease in SOC-S [9,58].

In this line, similar results are obtained by authors such as [59], who show in their study, under different uses and management, how in olive groves, over 30 years, there is a

50% loss of SOC-S under CT. These results also coincide with the studies carried out by [60], after 23 years in olive groves, which also show a decrease of around 40% of SOC-S caused to a large extent by CT management. On the contrary, Ref. [61] find that SOC-S varies as a function of soil depth. In many situations, CT or NT systems do not significantly differ in SOC content across profiles.

3.2. Soil Mineral Fraction Size Distribution

Referring to the distribution of the soil mineral fraction (SMF), i.e., the distribution of the different sizes of soil fractions, it is important to know how they are distributed and how they evolve over time, especially the fine SMF content (<20 µm: fine silt + clay) [11], as this is the fraction on which the SOC storage potential will depend [62]. As can be seen in Figure 3, the distribution followed by the coarse fractions (large macro-aggregates (>2000 µm) and small macro-aggregates (2000–250 µm)) in both periods and after 15 years of CT led to significant changes in SMF. Our results showed that the fraction of large macro-aggregates (>2000 µm) experienced a significant ($p < 0.05$) reduction in its percentage, from 12.7% to 6.7%, in the Ap horizon; however, there was a significant increase in depth in the Bw, BC, and C horizons, increasing in percentage from 6.5% to 9.9% in the Bw horizon, from 5.3% to 10.4% in BC, and from 6.5% to 19.9% in the C horizon. In the 2000–250 µm fraction, a significant reduction was observed, of 51.1%, 32.9%, 46.6%, and 50.6% (Figure 3), after 15 years of CT, for the Ap, Bw, BC, and C horizons, respectively. These results support the conclusion that the variations and losses could be attributed to the effect of CT and the lack of cover, which involve mechanical disruption of macro-aggregates. Authors such as [63] point out that intensively tilled soils in semi-arid Mediterranean areas are susceptible to degradation by losing their major fractions and being structured into minor fractions. Furthermore, authors such as [64] observed that, as a consequence of soil management with CT, there is a tendency towards the erosion of fine clay particles and organic matter, this management being responsible for the loss of surface stability [65,66]. This fact could indicate an acceleration of water erosion and a worsening of soil degradation [67] since, in these areas, water erosion rates are very high, becoming one of the leading causes of soil degradation [68]. However, Ref. [34] demonstrated, in their study carried out in the same area of traditional olive groves, that the change of management to NT with herbicides does not lead to an increase in the values of macro-aggregate fractions (large macro-aggregates (>2000 µm) and small macro-aggregates (2000–250 µm)), i.e., the removal of tillage and bare soils with herbicides does not lead to an improvement in total coarse fractions, and the lack of vegetation cover is, therefore, a determining factor.

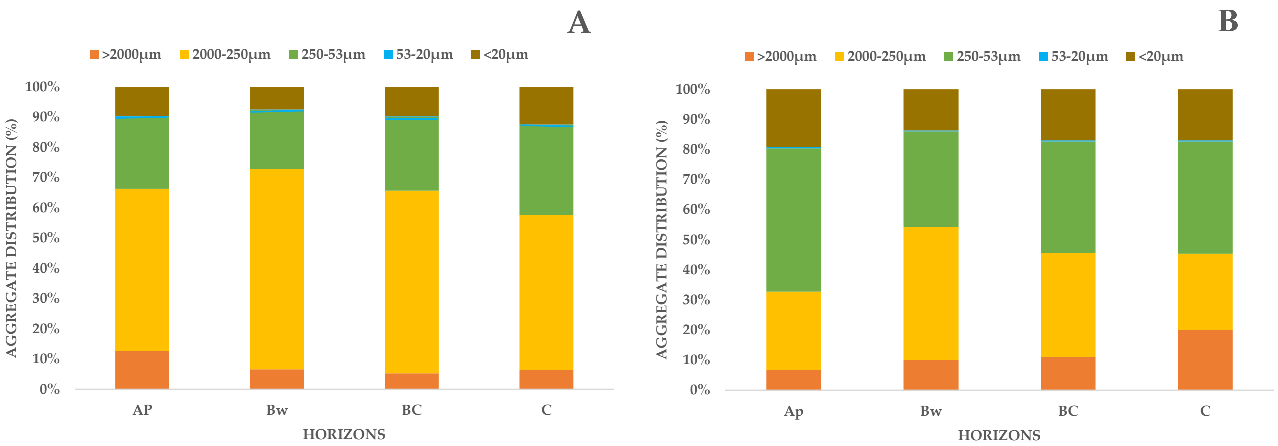

Figure 3. Percentage distribution of different soil aggregate size fractions as a function of different soil horizons according to the influence of conventional tillage over time. (**A**) CT0-2003; (**B**) CT1-2018.

The reduction in the coarse fractions implies a percentage increase in the fine fractions (large micro-aggregates (250–53 µm), silt + clay fraction (53–20 µm), and fine silt + clay

(<20 μm)), as can be seen in Figure 3. After 15 years, an increase in the percentages of the large micro-aggregates (250–53 μm), of 50.1%, 38.4%, 30.1%, and 20.2%, for the Ap, Bw, BC, and C horizons, respectively, was found. In the silt + clay fraction (53–20 μm), the increase was 51.2%, 45.2%, 38.9% in the Ap, Bw, and BC horizons, respectively, with no significant differences ($p < 0.05$) in the C horizon. Finally, in the fine silt + clay fraction (<20 μm), the increase was significant for the Ap, BC, and C horizons (50.1%, 38.8%, and 26.7%, respectively).

This increase in soil micro-aggregates (fine fractions) is due, on the one hand, to the prolonged effect of the CT in the study area, which caused a degradation of the soil structure, destroying the coarse fractions into smaller ones (micro-aggregates), and also causing the elimination of vegetation cover in the soil [69,70]. This lack of cover and the lack of vegetal debris in the soil caused a decrease in the amount of OM in the soils under study, which is a binding agent, thus facilitating the formation of fine fractions (micro-aggregates) due to the lack of binding of the coarse fractions (macro-aggregates). On the other hand, although clay content is a fundamental factor in soil aggregation [71] and in the soils studied the clay content is high, due to the CT, this content has been important for the formation of micro-aggregates [72] in the face of the destruction of the coarse fractions.

3.3. Evolution over Time of Soil Organic Carbon by Aggregate-Size Fractions and Its Distribution in Depth

Regarding SOC concentrations as a function of SMF (Figure 4), the values obtained in each of the soil fractions were low, reflecting the low SOC values obtained in the soils studied (Table 3) due to the semi-arid Mediterranean conditions and the intense monocropping system with CT, which cause degradation in the soils studied, with significant losses of soil through erosion. This fact, together with the absence of vegetation cover, leads to soil decarbonisation processes [73,74]. During the study period, it was observed that the lowest SOC concentrations according to the different soil fractions were located in the silt + clay fraction (53–20 μm) within the fine soil fractions (Figure 4). Authors such as [67] obtain equivalent results in their studies, supporting that lower SOC content is associated with micro-aggregates, with a decrease in SOC concentration with increasing profile depth [75]. This theory is also supported by [76] in a study conducted at 40 different sites with perennial crops and semi-arid conditions similar to our study area. After 15 years with CT in the olive monocrop area, no significant differences ($p < 0.05$) in SOC were observed in the different soil fractions, and only slight variations in SOC concentration within the fine and coarse soil fractions. Within the coarse soil fractions, a decrease in SOC concentration within the large macro-aggregate fraction (>2000 μm), of 38.6%, was observed in the Bw horizon (Figure 4). In the small macro-aggregates (2000–250 μm), an increase in SOC concentration over time, of 33.5%, was observed in the Ap and Bw horizons (Figure 4). Concerning the fine soil fractions, the SOC concentration in the large micro-aggregates (250–53 μm) increased over time by 57.1% at the surface (Ap horizon) and 40.8% at depth (BC horizon) (Figure 4). Finally, the fine silt + clay fraction (<20 μm) increased over time by 41.7% in the BC horizon (Figure 4). This increase in SOC in the fine soil fractions can be explained by the decomposition of labile OC fractions caused by CT, which breaks down soil macro-aggregates containing mostly labile OC. Therefore, this decomposition would increase and stabilize C in the small lower-sized classes (micro-aggregates) [77,78].

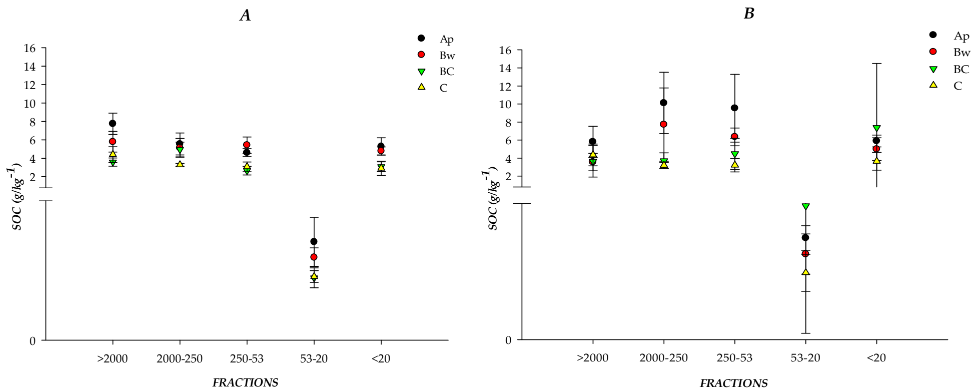

Figure 4. Soil organic carbon concentrations in aggregate size fractions as a function of different soil horizons according to the influence of conventional tillage over time. (**A**) CT0-2003; (**B**) CT1-2018.

3.4. Relationship between Soil Organic Carbon and Soil Mineral Fraction-Clay

In the present study, the evaluation of the relationship between SOC and SMF clay (<20 µm) (Table 4) is essential for analysing and quantifying SOC stabilisation in fine soil fractions [69]. This is because authors, such as [14], have showed mathematically the relationship between the SOC concentrations of the different soil fractions, which allows the expression of C saturation as C supply to the soil. Furthermore, this relationship is used as an indicator of the physical quality of the soil, establishing a value of 10 to determine the C storage capacity of the soil, i.e., below this value, soils are not able to store more SOC [79]. This established value is applied to different studies, such as that of [80], in other countries using 5 years of data from the National Soil Inventory of England and Wales, covering 3809 sites in cropland, grassland, and woodland.

Table 4. Soil Organic Carbon/Soil Mineral Fraction ratio in Mediterranean rainfed olive grove with conventional tillage in entire soil profile by horizons in the study area. (average ± SD) (n = 3).

Land Use	Hor	Depth (cm)	SMF/SOC ($g\ kg^{-1}$)	Δ (<20 µm) %
			<20 µm	Top/Sub soil
CT0	Ap	0–27.3	18.1 ± 1.2 Aa	
	Bw	27.3–55.6	15.7 ± 2.3 Aa	−13.7%
	BC	55.6–88.8	31.6 ± 2.1 Ba	+75.5%
	C	88.8–115.2	42.9 ± 1.6 Ca	+136.4%
CT1	Ap	0–32.7	32.7 ± 9.0 Ab	
	Bw	32.7–65.1	27.5 ± 3.4 Ab	−15.9%
	BC	65.1–89.8	21.7 ± 1.9 Bb	−33.6%
	C	89.8–120.0	46.7 ± 5.1 Ca	+43%

CT0 (2003) and CT1 (2018): Conventional tillage-centenary rainfed olive grove; Hor: Horizon; n: replications; SD: Standard deviation; SMF/SOC: Soil mineral fraction ratio/Soil organic carbon; Δ (<20 µm): Increasing and decreasing in the SMF/SOC ratio in the range <20 µm. Numbers followed by different capital letters within the same column have significant differences ($p < 0.05$) between depths considering the same land management. Numbers followed by different lower-case letters within the same column have significant differences ($p < 0.05$) between the same soil horizon and the same land management considering different periods of time.

On this basis, as shown in Table 4, in both periods, the values obtained exceed the value established by Dexter; therefore, our soils would have the capacity to function as a C sink both on the surface and at depth. The SMF/SOC ratio (Dexter Approximation) tended to increase at depth, except for the BC horizon in CT1, where there was a decrease (BC-CT0: 31.6 $g\ kg^{-1}$; BC-CT1: 21.7 $g\ kg^{-1}$). The evolution over time through the maintenance of CT has led to an increase in soil sequestration capacity in the first horizons, of 44.7% (Ap horizon) and 42.9% (Bw horizon), and a decrease at depth (BC horizon) of 31.3%. These variations in the Ap and Bw horizons were due to an increase in the finest fraction of the soil (<20 μm). Therefore, the effect of CT over time favoured an increase in the percentage of particles smaller than 20 μm, resulting in a favourable situation in 2018, when it would be more possible to store C in our soils on the surface but less favourable for storing at depth (BC horizon). Equivalent results have been obtained by [81], through a meta-analysis in their study, which revealed that the SMF/SOC ratio in grassland and cropland might decrease along with the deeper layers due to management conditions in the topsoil limiting the SOC storage capacity at depth. In addition, [82] found high SMF/SOC values (Dexter ratio) in perennial cropland areas in the shallow soil horizons across Europe, while the opposite results were observed in the deep horizons.

The decrease in storage capacity that occurred from 65 cm depth in the BC horizon happened as a consequence of the management used continuously over time, facilitating, among other factors, the leaching of soils, which impacts the SOC content in the deeper soil horizons (BC) within the finer soil fractions, with a loss in storage capacity of SOC in these fractions over time [83,84]. This indicates that although these soils were theoretically capable of storing more SOC at depth, tillage events involving the absence of vegetation cover, which is responsible for the contribution of OM to soils [85], would have reduced their storage capacity. The negative effect of CT on agricultural soils has been widely demonstrated, favouring erosion processes, soil structure degradation, and altering the quality and physical and chemical properties of soils [86]. For these reasons, authors such as [87–89] have suggested, in recent research in agroecosystems, that management practices such as NT, conservation tillage, minimum tillage, and the application of plant residues, are ideal as they increase the SOC and stabilise it in the medium term, making an important contribution to the recarbonisation and improvement of soil quality [23]. Furthermore, these management practices are more economical [90] than CT, as they reduce soil erosion and physical stress due to the lower intensity and depth of tillage, while retaining more stubble and plant debris. This provides an improvement in soil moisture conservation [91], soil structure [54,92], soil aggregate stability, and water permeability, [93] thus decreasing the risk of erosion [94,95]. Similarly, the European Union (EU) launched the EU Soil Strategy for 2030 to make soil an indispensable ally for climate change adaptation and mitigation [96]. In this sense, the new EU Soil Strategy sets out concrete measures to achieve net greenhouse gas removals for the land-use sector and land-use change. Therefore, on our soils, sustainable management practices (specific and continuous), such as the application of cover crops, crop rotation, agroforestry, prevention of conversion to arable land, diversification, and conversion to grassland, should be adopted, with many of these practices being profitable for the farmer [97]. Therefore, given that continued CT destroys soil macro-aggregates, which have a greater capacity to store carbon, as a consequence, soils are highly decarbonized. Therefore, they have an enormous potential to sequester carbon through sustainable management practices. This change in soil management practices would increase the proportion of soil micro-aggregates and the SOC sequestration capacity in this soil fraction, with this pool finding the greatest stabilisation over time.

3.5. Soil Organic Carbon Saturation and Deficit of Saturation

SOC saturation linked to the fine soil fraction (<20 μm) occurs when soil C can no longer continue to increase despite changes in production inputs or management, and it is impossible to accumulate and stabilise more C. As such, the soil can be considered saturated [78]. Furthermore, the fact that the ability of SMF to protect SOC is especially associated with the <20 μm fraction, stabilising SOC to reach saturation [98], is the reason why there is a strong relationship between stabilised SOC and soil fine particle content (<20 μm fraction). Based on these statements, the results obtained in Figure 5 showed how in the studied soils, the period of 15 years maintaining CT caused variations in the SOC_{sat} concentration and the SOC deficit (SOC_{def}) applied to the saturation concept.

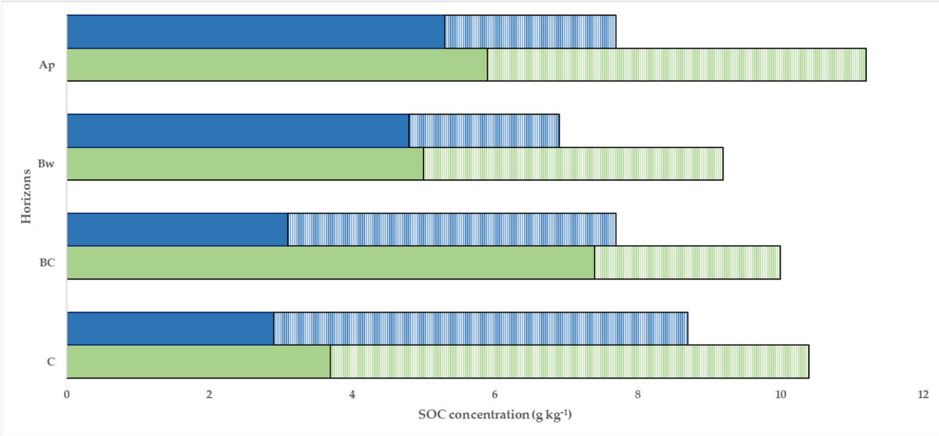

Figure 5. Soil organic carbon saturation value (SOC_{sat}) and current deficit (SOC_{sp}) as a function of different soil horizons according to the influence of conventional tillage over time. SOC_{sat}-CT0 (blue bars + blue bars with lattice); SOC_{sat}-CT1 (green bars + green bars with lattice); SOC_{sp}-CT0 (blue bars with lattice); SOC_{sp}-CT1 (green bars with lattice).

For the SOC_{sat} concentrations as a function of the <20 µm fraction, the values both in CT0 and in CT1 followed the same trend at depth, with significant differences ($p < 0.05$) between the different horizons. In both periods, a decrease in SOC_{sat} was observed in the Bw horizon (6.9 g kg^{-1} (CT0) and 9.2 g kg^{-1} (CT1)) concerning the superficial horizon, increasing again at depth (BC and C horizons) (Figure 5). After 15 years with CT, SOC_{sat} increased by 31.8%, 25.1%, 22.6%, and 16.2% in the Ap, Bw, BC, and C horizons, respectively (Figure 5). According to authors such as [99,100], this increase in sequestration capacity (SOC_{sat}) is conditioned by the increase in SOC concentrations linked to the fine fraction (<20 µm), especially at depth, produced by the vertical movement of dissolved OM as a consequence of soil management, which causes its translocation from the surface to deeper areas of the soil. In addition, [101] place fauna and deep root systems as drivers of the increase in SOC linked to the fine fraction at depth, impacting SOC_{sat} concentrations and, therefore, sequestering.

Based on the data obtained for SOC_{sat} and considering the SOC in the fine fraction, the SOC_{def} was determined, which is conditioned by the previous values. In CT0, SOC_{def} concentrations were similar in the first soil horizons (Ap and Bw). However, the trend changed at depth, increasing SOC_{def} concentrations (BC: 4.6 g kg^{-1}; C: 5.8 g kg^{-1}). In CT1, the trend was the same as CT0 in the shallow horizons, with similar concentrations in Ap and Bw. On the contrary, there was a decrease in SOC_{def} concentrations in the BC horizon (BC: 2.6 g kg^{-1}), increasing these concentrations in the deeper C horizon (C: 6.7 g kg^{-1}). In the medium term, the effect of CT on our soils caused an increase in surface SOC_{def}, of 55.6% and 50.1% for the Ap and Bw horizons, respectively, and a decrease of 43.1% in the BC horizon, but no significant differences were observed in the deepest horizon (C) (Figure 5). These results showed that these soils could behave as carbon sinks and could still store an average of 35.7% more of the stabilised SOC <20 µm than the soils under study. This increase in storage capacity is due to the increase in the saturation capacity (SOC_{sat}) of the soil mentioned above for the Ap, Bw, BC, and C horizons that occurred after 15 years, as a consequence of the increase in the percentages of the <20 µm fraction for the different soil horizons (Figure 3), thus directly conditioning the stabilisation capacity and C sequestration. Although there is an increase both in SOC_{sat} and in $SOC_{def,}$ soil C sequestration thresholds were low due to the semi-arid conditions of the Mediterranean area [102] and the rapid mineralisation of C rather than its incorporation into soil micro-aggregates [78,99,103]. However, if good agricultural practices, such as crop residues, cover crops, and compost, are applied to these soils, it may be possible to further increase the sequestration and sink potential in these soils.

3.6. Carbon Sequestration Potential in the Medium Term

Potential carbon sequestration linked to the <20 μm fraction in soils is influenced by several factors, including soil type. This is a critical factor that significantly affects SOC accumulations, along with the profile, up to an average depth of 70 cm [104]. In our study, mean values up to 89.8 cm depth (Ap, Bw, and BC horizons) of 80.5 Mg ha^{-1} in CT0 and 102 Mg ha^{-1} in CT1 (Figure 6) were obtained. Authors such as [89] obtain mean values estimating the same depth in Cambisols of 111.6 Mg ha^{-1}, being similar and comparable to those of our study. However, the medium term (2003–2018) with CT generated variations in the saturated soil organic carbon stock (SOC-S_{sat}) linked to the finest fraction of soil (<20 μm), along with the complete soil profile (120 cm), where an overall increase in SOC-S_{sat} storage capacity of 38% and 28.7% was observed in the Ap and Bw horizons, respectively, and 23.8% in the C horizon (Figure 6). Therefore, the T-SOC-S_{sat}, after 15 years, experienced an increase of 30.5 Mg ha^{-1}, considering the whole profile, of which 15.9 Mg ha^{-1} accumulated at the surface (Ap) and 14.6 Mg ha^{-1} at depth (Bw, BC, and C) (Figure 6). These results showed that the clay fraction (<20 μm) positively affected SOC-S storage by protecting it from microbial attack [105]. Furthermore, [106] explained in their work how the increase in sequestration capacity (SOC-S_{sat}) is conditioned by the increase in SOC-S concentrations bound to the fine fraction over time due to the effect of ploughing on the soil, which causes an improvement in the mixture of input and soil organic materials, leading to an increase in C mineralisation rates.

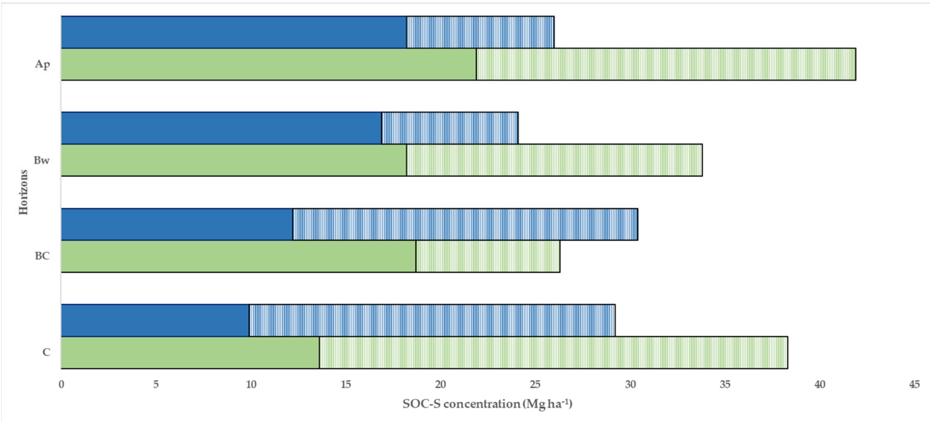

Figure 6. Potential soil organic carbon stock sequestration (SOC-S_{sat}) and current soil organic carbon stock deficit (SOC-S_{sp}) as a function of different soil horizons according to the influence of conventional tillage over time. SOC-S_{sat}-CT0 (blue bars + blue bars with lattice); SOC-S_{sat}-CT1 (green bars + green bars with lattice); SOC-S_{sp}-CT0 (blue bars with lattice); SOC-S_{sp}-CT1 (green bars with lattice).

These results conditioned the soil organic carbon stock deficit (SOC-S_{def}), where T-SOC-S_{sp} values of 52.6 Mg ha^{-1} were obtained in CT0 and 67.8 Mg ha^{-1} in CT1 (Figure 6). In other words, these results showed that the period studied with CT caused an increase in the capacity of the soil to potentially sequester carbon of 15.2 Mg ha^{-1} in 15 years, with an average increase in surface area of 12.2 Mg ha^{-1} (Ap) and 3.1 Mg ha^{-1} at depth (Bw, BC, and C). This increase in sequestration capacity is due to the increase over time in the percentage of the fraction bound to <20 μm, thus affecting the increase in sequestration capacity (SOC-S_{sat}) and the SOC-S deficit (SOC-S_{sp}). According to studies such as that of [107], this increase in medium term sequestration capacity may be due to the effect of tillage on the redistribution of the percentages of the different soil fractions, providing an increase in the rate linked to the fine fraction of the soil. However, it should also be considered that the effect of tillage on soils causes a slow accumulation of SOC bound to this fraction, which would explain why low values are obtained even though there is an increase in sequestration capacity [89].

Finally, it is worth noting the medium term effect of this type of analysis when looking at saturated carbon and the storage potential of the soil. Accordingly, [108] underline the fundamental role of medium term experiments, considering time frames of 43–50 years. Therefore, since the analyses in our study were conducted over 15 years, variations over this period could change and affect the concept of saturation and potential soil storage differently over a more extended period.

4. Conclusions

This study investigated the medium term effects of CT on the carbon storage capacity (carbon saturation) of olive soils in Mediterranean areas. In this way, we intended to determine the soil sequestration capacity and how the CT management in the medium term (15 years) affected the soil role of C sinks.

The CT significantly affected the aggregates' distribution by reducing the fractions of small macro-aggregates (2000–250 μm) and shifting the aggregate size towards smaller particles, increasing their percentage.

Concerning SOC fractionation, there was an increase of SOC in the fine fractions (micro-aggregates) of the soil due to the effect of CT over time, breaking down soil macro-aggregates.

Furthermore, focusing on SOC bound to the <20 μm fraction, where C stabilisation occurs, the effect of continued CT affects the sequestration capacity over 15 years with an increase in the first horizons (Ap and Bw) and a decrease at depth (BC horizon).

Finally, the continued effect of CT in the medium term led to an increase in C sequestration capacity by increasing concentrations both in T-SOC-S_{sat} and in SOC-S_{def}.

In conclusion, the results obtained show that the effect of CT in the medium term caused degradation in the soils studied; because of this, after 15 years, although there have been generalized increases both in in the percentage and the SOC content in the fine fractions (micro-aggregates), the soils were far from SOC saturation and showed a high capacity to sequester carbon and stabilize it. Therefore, if sustainable management practices were applied in the studied soils, they could potentially contribute to carbon sequestration and storage, favoring climate change mitigation and adaptation, as the soils have been degraded by the heavily mechanized management that has up to now been employed.

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