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Effects of Management and Hillside Position on Soil Organic Carbon Stratification in Mediterranean Centenary Olive Grove

Jesús Aguilera-Huertas, Beatriz Lozano-García [ID], Manuel González-Rosado [ID] and Luis Parras-Alcántara *[ID]

SUMAS Research Group, Department of Agricultural Chemistry, Soil Science and Microbiology, Faculty of Science, Agrifood Campus of International Excellence—ceiA3, University of Cordoba, 14071 Cordoba, Spain; a52aghuj@uco.es (J.A.-H.); a72logab@uco.es (B.L.-G.); mgrosado@uco.es (M.G.-R.)
* Correspondence: luis.parras@uco.es; Tel.: +34-957211092

Abstract: The short- and medium—long-term effects of management and hillside position on soil organic carbon (SOC) changes were studied in a centenary Mediterranean rainfed olive grove. One way to measure these changes is to analyze the soil quality, as it assesses soil degradation degree and attempts to identify management practices for sustainable soil use. In this context, the SOC stratification index (SR-COS) is one of the best indicators of soil quality to assess the degradation degree from SOC content without analyzing other soil properties. The SR-SOC was calculated in soil profiles (horizon-by-horizon) to identify the best soil management practices for sustainable use. The following time periods and soil management combinations were tested: (i) in the medium-long-term (17 years) from conventional tillage (CT) to no-tillage (NT), (ii) in the short-term (2 years) from CT to no-tillage with cover crops (NT-CC), and (iii) the effect in the short-term (from CT to NT-CC) of different topographic positions along a hillside. The results indicate that the SR-SOC increased with depth for all management practices. The SR-SOC ranged from 1.21 to 1.73 in CT0, from 1.48 to 3.01 in CT1, from 1.15 to 2.48 in CT2, from 1.22 to 2.39 in NT-CC and from 0.98 to 4.16 in NT; therefore, the soil quality from the SR-SOC index was not directly linked to the increase or loss of SOC along the soil profile. This demonstrates the time-variability of SR-SOC and that NT improves soil quality in the long-term.

Keywords: soil profile; cover crops; tillage systems; land use; chronosequence; soil organic carbon; soil quality

1. Introduction

The soil is the most superficial layer of the earth's crust, altered by weathering and conditioned by soil physicochemical properties [1]. It is a basic constituent of terrestrial ecosystems and an essential component for the sustainable development of life on earth [2], being fundamental for food production [3]. Furthermore, it constitutes the most diverse and important ecosystem on the planet, characterized by its biological biodiversity [4] and conditioned by the soil biota, with direct and indirect effects on crop growth, the sustainability of soil productivity, and the nutrient cycle quality [5]. For all these reasons, the soil is the foundation of all terrestrial ecosystems, and most of the ecosystem services necessary for human survival arise from it [6]. Moreover, soil ecosystem services depend on soil health and soil biota biodiversity [7], influenced by the physicochemical soil properties and the interactions between land use and management. In this sense, some researchers [8] have indicated that the "soil health" definition is close to the "soil quality" concept [9]. Therefore, soil quality is a primary topic of study to evaluate the soil degradation degree and to identify management practices for sustainable land use, considering physical, chemical, and biological parameters [10]. In this context, the soil quality concept is related to the soil degradation problem, which implies a decrease in soil quality with a reduction in its functions and ecosystem services [1].

The major indicators linked to soil quality are the erosion process and the reduction of soil organic carbon (SOC)—soil organic matter (SOM) [11]. The SOC-SOM content is the most important indicator in soil degradation processes [12] since erosion processes depend on the SOC-SOM content. In addition, a SOM reduction normally implies a SOC loss in mineral soils, affecting salinization, biodiversity, erosion, desertification, floods, landslides, biomass production, soil filtering, and so on [13]. Although we should not generalize, there are authors [12,14,15] who provide specific data (e.g., a reduction of 1% of SOM content implies a 10-40% decrease in aggregate stability, a reduction from 4% to 2% of SOM implies a 50% increase of predicted soil loss by water erosion, a reduction of 1% of SOM content implies a 1–2% decrease in macroporosity, a reduction from 7% to 3% of SOM implies a > 10% reduction of water retention and a reduction from 5% to 2% of SOM implies a 90% decrease of microbial biomass). Therefore, the SOC analysis in different land uses and management practices constitutes a valuable indicator of soil quality [16].

In this context, soil depth is a very important aspect [17]. SOC studies are normally limited to 1 m in depth, although there are authors who have conducted studies at greater depths [18]. In this sense, it is important to note that in the scientific community, there is no consensus on the soil depth when the SOC distribution is studied [19]. Therefore, there are uncertainties when comparing data at different scales [20]. Hence, when studies of soil evolution are carried out over the medium term (10–30 years) [21] or longer periods, we should use soil profile (if it is possible). In this line, some researchers [22] have shown that the SOC accumulation in surface (topsoil) is important for soil quality improvement (erosion control, water infiltration, conservation, and nutrient supplementation) without forgetting the SOC at depth. Consequently, we can differentiate two SOC levels (topsoil and subsoil), and the relationship between the surface and depth of SOC content could be used as a soil quality indicator in agricultural soils under different land management methods [23,24]. This relationship is called the SOC stratification ratio (SR-SOC). The SR-SOC is based on the idea that the SOC content at depth is used as a baseline to normalize the SOC evaluation. Therefore, the SR-SOC is common in many natural, and managed ecosystems depend on the C inputs and decreases with soil depth [23].

In Mediterranean areas, the olive grove (OG) is the main land use [25], and Spain is the country with the highest production of olive oil in the world (producing around 47% of the world's total olive oil) [26]. The OG expansion in the Mediterranean Basin is due to the climatic conditions, but its development has adverse effects on the soil, like a reduction in soil infiltration rate [27], low soil aggregate stability [28], OM depletion, soil structure degradation, and high soil loss [29]. Therefore, it is necessary to improve the soil's physical quality [30] in order to increase sustainable land use and reduce land degradation processes [31]. In fact, soils with good physical quality have the ability to support crops properly and reduce land degradation [32].

Traditional management in Mediterranean OG is marked by (i) low SOM content (<2%) [33] due to high temperatures and low rainfall that allow the SOM mineralization, (ii) low plant density, which facilitates the soil loss [34], (iii) intense tillage—heavily machined [35], and (iv) the landscape, formed by steep hillsides with slight changes in concavity and convexity [36]. These four factors, acting synergistically, can cause losses in soil quality, with significant environmental implications [37]. Given this scenario, conventional OG is associated with soil degradation problems [38]. Consequently, reducing tillage and acting in the vegetation cover can increase soil quality [39]. Moreover, the hillside position can affect the temperature and humidity of the soil due to the insolation differences influencing soil microclimate [40], conditioning the plant community's distribution and the soil formation processes [41]. Therefore, the temperature regime, vegetation, and soil water content can affect the microorganisms' activity, either delaying or accelerating the SOC decomposition [42].

One of the most accepted management techniques to reverse soil degradation processes in traditional Mediterranean OG is the use of cover crops [43,44] in the middle of the OG street so that the cover crops can act as a physical barrier, reducing sediment

delivery runoff and nutrient losses and increasing infiltration rates [45,46]. Therefore, by combining minimum or no-tillage operations with cover crops and plant residues, the SOM input can be facilitated, improving soil structure and reducing soil degradation and soil loss [47]. In addition, cover crops can improve the biological activities involved in soil health, nutrient cycling, and crop production [48], without forgetting that crop residues being used as mulch can favor surface aggregates formation and prevent crust formation and pore sealing. Reducing tillage, the use of cover crops, and the plant residues generated can increase the SOM content through crop diversification, improving the soil properties. These agricultural practices are a key factor in improving soil quality [49,50].

The principal objective of this research was to study the soil quality from the soil organic carbon content and the carbon stratification index in soil profiles of traditional Mediterranean olive groves (centenary) in different scenarios: (i) analyzing land management change effects (conventional tillage to no-tillage) in the medium-term (17 years), (ii) studying the land management change effects (conventional tillage to no-tillage with cover crops) in the short-term (2 years), and (iii) assessing the effect of cover crops in three topographic positions of a hillside in the short-term (2 years) in a Mediterranean rainfed olive grove.

2. Materials and Methods

2.1. Description of the Study Area and Experimental Design

The study area is located on an experimental farm with OG in Garcíez (Torredelcampo, Jaén) in the south of Spain (37°50′20″ N—3°52′32″ W) (Figure 1). The main characteristics of the study area are described in Table 1. The experimental farm was a centenary rainfed OG of the Picual variety (*Olea Europaea*) with traditional management—conventional tillage (CT) strongly mechanized (an average density of 90 trees ha^{-1}—each tree had two trunks; tree spacing 12 m × 12 m; tree size—3 m high × 6 m canopy diameter), in a hillside with the same topographic orientation (northeast). The study was conducted on soil profiles (horizon by horizon) [26]. The different land managements and land operations at the experimental farm are described in Table 2.

At the beginning of the 20th-century, the studied farm was planted with olive trees. Between 1950 and 2003, soil management was conventional tillage (Table 2). The research began in January 2003, and the latest data were obtained in September 2019. In 2003, the study farm was divided into two parts, with two land managements: conventional tillage (CT0) and no-tillage (NT0) (2003–2019) (medium-long-term, 17 years). In 2017, the farm with CT0 was divided in two, and another land management change (LMC) took place: CT1 and no-tillage with cover crops (NT-CC) (2017–2019) (short-term, two years) (Figure 2).
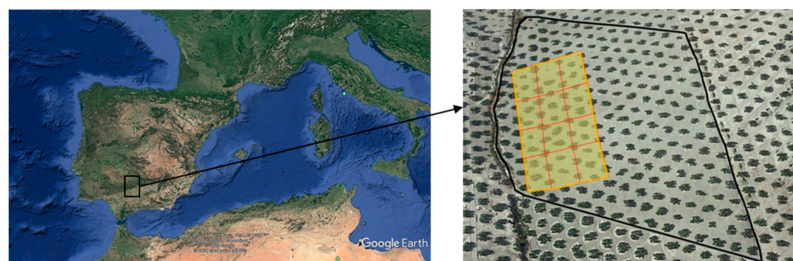

Figure 1. Study area. Garcíez-Torredelcampo (Jaén-Spain)—(37°50′20″ N—3°52′32″ W). Source: author elaboration; folder © 2020 Google. https://www.google.es/maps/@37.8499263,-3.8650632,1 62m/data=!3m1!1e3 (accessed on 1 September 2020).

Table 1. Main characteristics of the study area.

Parameter	Description
Location	Torredelcampo—Jaén, South of Spain
Coordinate	37°50′20″ N—3°52′32″ W
Altitude	Average (541 m.a.s.l)—(from 530 m.a.s.l to 593 m.a.s.l)
Slope	<8%
Epoch and lithology [a]	Miocene loam and marlaceous lime
Morphogenesis [b]	Denudative—formed by hills
Hydrology [b]	Dendritic network of carbonate facies [b]
Climatic classification [c]	Mediterranean—Csa
Climatic characteristics [d]	Average annual rainfall: 493.2 mm Average annual temperature: 17.1 °C—(maximum: 46.2 °C (August); minimum: −7.8 °C (January)) Relative humidity: 59%—insolation: 237 h month^{-1}—wind speed: 6 km h^{-1}—humidity index: 0.50 Rain erosivity: highly variable (from 2.1 to 75)—5 months with frost risk
Soil type [e]	Calcaric Cambisols—Cmca
Principal soil properties [f]	Deep soils: 123.8–128.7 cm—texture: clayey soils—basic pH (>7)—low SOM content
Principal soil characteristics [g]	Low fertility—poor physical conditions—low capacity for agricultural use

[a] [38]; [b] [51]; [c] [52]; [d] [53]; [e] [54]; [f] [55]; [g] [18]; m.a.s.l: meters above sea level.
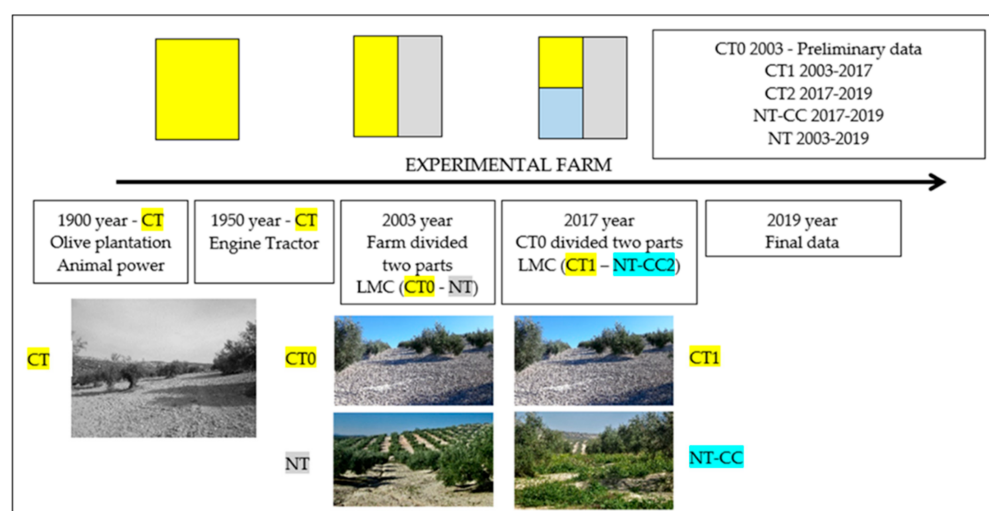

Figure 2. Period of the study farm. LMN: land management change; CT: conventional tillage; CT0: conventional tillage 2003; NT: no tillage; CT1: conventional tillage 2017; and NT-CC: no tillage with cover crops 2017.

In addition, between 2017 and 2019, three vegetation cover types were used in OG to study crop diversification, its effect on the soil, and the productivity ratio in Mediterranean rainfed OG (one of the objectives of the Diverfarming project—European Commission Horizon 2020—grant agreement 728,003). The cover crops on the OG streets were oats (*Avena sativa*), saffron (*Crocus sativus*), and lavender (*Lavandula × intermedia*), and the seed quantities used were 140 kg ha^{-1}, 2000 kg ha^{-1}, and 12,000 plants ha^{-1} for oats, saffron, and lavender, respectively. The three crop diversifications (saffron, oats, and lavender) were initially planted between the OG streets, but due to external factors like low rainfall, high temperatures, and high rabbit (*Oryctolagus cuniculus*) numbers, these diversifications were not fully developed and were not profitable during the period considered (two years); therefore, these cover crops were colonized by spontaneous vegetation (*Conyza canadensis, Arenaria hispanica, Sonchus oleraceus, Capsella bursapastoris, Diplotaxis virgata, Raphanus raphanistrum*, etc.) and the result was a mixed cover formed of saffron, oats, and lavender with the intercropping of spontaneous vegetation.

These LMCs allowed us to establish comparisons between the soil quality in four senses: (a) first, the soil quality evolution under conventional tillage (CT) between 2003 and 2019 (medium-long-term: CT0-2003; CT2-2019), (b) second, LMC from CT to NT between 2003 and 2019 (medium-long-term: CT0-2003; NT0-2019), (c) third, between 2017 and 2019 (short-term) in CT (CT1-2017; CT2-2019), and (d) finally, the soil quality evolution between 2017 and 2019 (short-term) after the LMC from CT to NT-CC (2017-CT1; 2019-NT-CC). In addition, as the study surface was not fully horizontal (characteristic of Mediterranean areas), it was decided to analyze the physical and chemical soil changes along the hillside (<5% slope) in different topographical positions: summit (S), backslope (B), and toeslope (T).

Table 2. Land management, periods, and duration on the experimental farm.

Period	Management	Duration	Management Description
1900–2003	CT [a]	1900–1950	Systems using animal power (plow with mules) with lightweight reversible plows; nonmineral fertilization or pesticides.
		1950–2003	Annual passes with disk harrow and cultivator in the spring, followed by a tine harrow in the summer (tractor services for land preparation). Mineral fertilization was applied (100 kg ha^{-1}—urea, 46% N).
2003–2019	Farm is divided into two parts: first LMC (CT0 and NT0)	2003 (January) CT0 to 2019 (September) CT2 and NT0	CT0 and CT2—conventional tillage (heavily tilled). After the olive harvest, 180 kg ha^{-1} of mineral fertilizer (urea, 46% N) is applied in alternate years. Afterward, the olive trees are pruned, the pruning remains are crushed and added to the street among the olive trees (6 Mg ha^{-1}), and fungicides are applied (Copper oxychloride 34.5% w.p.). After an annual pass with a disk harrow (25 cm) and cultivator in the spring, a tine harrow is used in the summer to decrease the size of the clods. Finally, a broad-spectrum herbicide is used in the autumn to control weeds under the trees and allow the harvest of the olives.
			NT0—no tillage/reduced tillage. No tillage implies the same application of pruning residues, fertilizers, fungicides, and herbicides, but NT was managed without tractor use.
2017–2019	Second LMC: the farm with CT0 is divided into two parts (CT1 and NT-CC)	2017 (September) to 2019 (September)	CT1 is similar to CT0
			NT-CC—no tillage/reduced tillage (is similar to NT0) with cover crops.

CT [a]: conventional tillage (there are no data available on the physical and chemical soil properties for 1950–2003); LMC: land management change; CT0: conventional tillage 2003; NT: no tillage in 2003; CT1: conventional tillage 2017; NT-CC: no-tillage with cover crops 2017.

2.2. Soil Sampling and Analytical Methods

Samples from 33 soil profiles were collected: three from CT0 at the beginning of the experiment (January 2003), nine from CT1 at the intermediate situation of the experiment (September 2017), nine from CT2, nine from NT-CC, respectively at the end of the experiment (September 2019) (three from each topographical position (S—B—T) in both cases (CT2 and NT-CC)) and three in NT0 (September 2019).

In the short-term comparison (2017–2019), 12 plots from different topographical positions (four from S, four from B, and four from T) on the hillside were selected for the study: three plots with CT and nine plots with NT-CC (three plots in S, three in B and three in T position). In each topographic position, the observation area was 400 m^2 (20 m × 20 m). At each sampling point, the main topographic variables (altitude and slope) were measured.

Soil samples were collected along the different soil horizons for each profile, thus avoiding mixing the pedogenic horizons and allowing for a proper determination of physical and chemical soil properties [56–58]. A random sampling scheme was adopted, pits were dug with a mini-excavator, and samples were collected. Soil samples were 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. Three repetitions were carried out for each sample. The analytical methods, laboratory analysis, and other parameters calculated used in this study to determine different soil properties are reported in Table 3, according to the Handbook of Plant and Soil Analysis for Agricultural Systems [59].

Table 3. Analytical methods used in this study (field measurements, laboratory analysis, and parameters calculated).

Parameters	Method
Field measurements	
Bulk density (Mg m^{-3})	Core method [60] [a]
Laboratory analysis	
Particle size distribution	Robinson pipette method [61] [b]
pH—H$_2$O	Suspension in water 1:2.5 [62]
Organic C (g kg^{-1})	Walkley and Black method [63]
Total N (g kg^{-1})	Kjeldahl method [64]
Parameters calculated from analytical data	
SOC-S (Mg ha^{-1})	SOC-S = SOC concentration $\times$ BD $\times$ d $\times$ (1 $-$ δ2mm%) $\times$ 10^{-1} [65,66] [c]
T-SOC-S (Mg ha^{-1})	T-SOC-S = Σ soil horizon 1 … n SOC-S soil horizons [66] [d]
SR	SRs (SR1(S1/S2), SR2 (S1/S3) and SR3 (S1/S4)) [23] [e]

For all the parameters studied, the recommendations of the *Handbook of Plant and Soil Analysis for Agricultural Systems* were followed [59]. [a] 3 cm in diameter, 10 cm in length, and 70.65 cm^3 in volume; [b] Prior to the determination of particle size distribution, samples were treated with H$_2$O$_2$ (6%) to remove organic matter (OM). Particles larger than 2 mm were determined by wet sieving, and smaller particles were classified according to [60]; [c] where SOC is the organic carbon content (g kg^{-1}), d is the thickness of the soil layer (cm), δ2 mm is the fractional percentage (%) of soil mineral particles >2 mm in size in the soil, and BD the soil bulk density (Mg m^{-3}); [d] T-SOC-S: total SOC stock determined by adding all the soil horizons considered; [e] SR: stratification ratio. The SR is defined as a soil property on the soil surface divided by the same property at a lower depth. In this study, we defined three SRs (SR1(S1/S2), SR2 (S1/S3), and SR3 (S1/S4)).

2.3. Statistical Analyses

The effect of land management, topographical position and depth on soil properties was analyzed using ANOVA (SPSS 13.0 for Windows). Data were tested for normality to verify the model assumptions, and differences of $p < 0.05$ were considered statistically significant.

3. Results and Discussion

3.1. General Properties of the Studied Soil

The soils in the study area can be characterized as Calcaric Cambisols (CMca), quite clayey with a silty clay loam texture [18], which in certain circumstances give a vertic character [54], with some differences in physicochemical properties according to the management (CT, NT, or NT-CC) and topographic position (S, B, or T) [67]. These soils are formed from the bedrock (marl and marlaceous lime), and their development is conditioned by limestone genesis (conditioned by the Ca^{2+} ions) [68], although the hillside position can also affect their development, especially when the land management is very aggressive (strongly mechanized). They are young soils, developed on corrugated hillsides, well-drained on the surface due to the high gravels and stone content, with little chemical fertility, physically poor, and a low capacity for agricultural use [18,37,55].

The gravel content was very homogeneous, ranging from 12.6% (C horizon) to 17.7% (Bw/C horizon), and the tendency was to increase in depth, except for the C horizon, which decreased (Table 4). In this line, various interpretations can justify this abnormal behavior: (i) by a stone line presence [69] on the Bw/C horizon due to plowing depth, (ii) the tillage used (CT) does not remove large stones and boulders [70] at depth (C horizon), and (iii) a

combination of both. Texturally, the soils were silty clay loam, with few differences in silt and clay content at depth (Table 4); this particle distribution increases the surface runoff, reduces the infiltration rates, and increases the runoff discharge, sediment concentrations, and erosion rates, worsening the water percolation and increasing the erosion by curbing erodibility and runoff [71]—processes especially important when the topography is not flat (undulating hillsides, as happens in the study area).

With regard to bulk density (BD) and pH, these increased along with depth. It is important to highlight that soil pH is conditioned by topography, climate, and lithology; therefore, in hillsides with calcareous lithology and semiarid conditions, the pH should increase with depth [72] due to the alteration processes of the bedrock.

With respect to SOM concentrations, they are very low, decreasing with depth and ranging from 1.22% (A horizon) to 0.71% (C horizon). These low SOM concentrations can be explained by the climatic conditions [73], the high OM mineralization, the lack of crop residues after periods of drought [24], and degradation processes due to the vegetation loss and unsustainable soil management causing an impoverishment of the SOM content. The most important consequence of this low SOM content is the reduction of soil physical protection, favoring erosion and accelerating the SOM decomposition due to CT [74,75]. However, apart from these negative effects, the SOC content and SOC stock (SOC-S) concentrations may be affected, too. On average, the SOC-S in the study soils is 67.2 Mg ha^{-1} (for 115.7 cm depth), far below the values obtained at World level [76] in CMca (71 Mg ha^{-1} for 1 m depth), at the European scale [77] in cropland (106 Mg ha^{-1} for 30 cm depth), for Spain in CM [78] with OG (71.4 Mg ha^{-1} for 1 m depth), for Andalusia in CM [79] with permanent crops (59.9 Mg ha^{-1} for 75 cm depth), and for OG with CT [80] in Jaén (61.53 Mg ha^{-1} for 30 cm depth). The situation in Mediterranean areas is considered high-risk [81,82], so regions like Andalusia are classified as "high erosion risk zones" with a mean annual soil loss of 23.2 Mg ha^{-1}, causing a significant impact on SOM and SOC levels [44], affecting SOC-S, and inducing decarbonization processes in the soil [83].

Table 4. Principal soil properties evaluated (average $\pm$ SD) in the soil profile by horizons in the study area. Preoperational stage, CT0 (January 2003). Data are means $\pm$ SD (n = 3).

Hor	Depth (cm)	TH (cm)	Gravel (%)	Texture (USDA)	Sand (%)	Coarse Silts (%)	Fine Silts (%)	Clay (%)	BD (Mg m^{-3})	Ph (H$_2$O)	OM (%)	SOC (g kg^{-1})	SOC-S (Mg ha^{-1})	TN (g kg^{-1})	TN-S (Mg ha^{-1})	C:N
Ap	0–19.3	19.3 $\pm$ 2.1	12.8 $\pm$ 1.7 a	SCL	8.7 $\pm$ 0.6 a	7.3 $\pm$ 1.5 a	52.5 $\pm$ 2.4 a	31.5 $\pm$ 0.9 a	1.41 $\pm$ 0.03 a	7.7 $\pm$ 0.1 a	1.22 $\pm$ 0.06 a	6.44 $\pm$ 0.30 a	15.3 $\pm$ 0.6 a	0.93 $\pm$ 0.15 a	2.21 $\pm$ 0.33 a	7.0 $\pm$ 0.8 a
Bw	19.3–56.0	36.7 $\pm$ 7.6	13.6 $\pm$ 1.6 a	SCL	5.5 $\pm$ 1.6 b	9.2 $\pm$ 1.4 a	53.7 $\pm$ 1.9 a	31.6 $\pm$ 0.6 a	1.42 $\pm$ 0.02 a	8.0 $\pm$ 0.1 a	1.01 $\pm$ 0.05 a	5.32 $\pm$ 0.18 a	23.9 $\pm$ 0.8 b	0.93 $\pm$ 0.05 a	4.19 $\pm$ 0.27 b	5.7 $\pm$ 0.5 b
Bw/C	56.0–89.0	33.0 $\pm$ 10.8	17.7 $\pm$ 1.2 b	SCL	1.8 $\pm$ 0.8 c	11.0 $\pm$ 1.7 b	53.9 $\pm$ 1.8 a	33.3 $\pm$ 1.9 a	1.43 $\pm$ 0.03 a	8.1 $\pm$ 0.1 a	0.76 $\pm$ 0.04 b	4.08 $\pm$ 0.19 b	15.5 $\pm$ 0.7 a	0.87 $\pm$ 0.05 a	3.36 $\pm$ 0.25 b	4.6 $\pm$ 0.2 b
C	89.0–115.7	26.7 $\pm$ 12.6	12.6 $\pm$ 0.6 a	SCL	4.1 $\pm$ 0.9 b	14.0 $\pm$ 1.6 c	52.9 $\pm$ 1.6 a	29.0 $\pm$ 0.8 a	1.44 $\pm$ 0.02 a	8.1 $\pm$ 0.1 a	0.71 $\pm$ 0.02 b	3.72 $\pm$ 0.11 b	12.5 $\pm$ 0.4 a	0.77 $\pm$ 0.05 b	2.58 $\pm$ 0.21 a	4.9 $\pm$ 0.4 b

CT0: conventional tillage (Preoperational stage, Initial situation, January 2003). SD: standard deviation; Hor: horizon; TH: thickness; SCL: silty clay loam texture; BD: bulk density; OM: organic matter; SOC: soil organic carbon; SOC-S: soil organic carbon stock; TN: total nitrogen; TN-S: nitrogen stock; C:N: carbon-nitrogen ratio. Numbers followed by different lowercase letters in the same column have significant differences ($p < 0.05$) considering different depths.

3.2. Soil Depth Conceptualization: Soil Profile Is Required when SR Is Used as a Soil Quality Indicator in OG

The studied soils were not very deep (115.7 cm on average) (Table 4); similar results have been found [84] in other CM in rainfed OG in Jaen province, with no significant difference *(p < 0.05)* regarding the soil depth in the range 119.7–128.7 cm and limited by rock fragments.

It is reasonable that the SR-SOC should not be measured only superficially because deeper roots can be found at lower depths [85] and because the management practices and land use can affect the SOC in depth [86]. Some studies show that, by six years of age, olive trees develop roots with a 1 m depth and maximum diameters of 27 mm, covering areas of 13.8 m^2 per tree [87]. In this sense, when measuring the SOC sequestration, stock, and loss, it is necessary to integrate all the SOC in the root zone (1 or 2 m deep) [85]. Consequently, it is necessary to study the soil profile [38] so that the SOC variability at lower depths is influenced by vertical processes [88,89], especially in temperate climates, where large amounts of SOC can accumulate below depths of 30 cm [90]. Most studies tend to focus on the top 30 cm or 1 m of soils and, therefore, underestimate the total SOC, affecting the SR calculation. In this respect, it is evident that the sampling approach used can affect the SOC quantification [91]. Hence, the SOC should be inventoried by genetic horizon using the soil profile approach, assuming that the term soil profile refers to "a vertical section of the soil through all its horizons and extending into the C horizon" [92].

3.3. Stratification Ratio of SOC and N at the Beginning of the Research (January 2003)

The starting point research was January 2003 in a Mediterranean rainfed OG with CT (heavily mechanized). A detailed analysis of the SOC content in the study area tells us (Figure 3) that there is: (i) a SOC reduction at depth due to the deeper horizons being conditioned by the OM entry in topsoil and because the greatest OM contributions are in the form of fine roots, root exudates, and dissolved organic carbon [93], (ii) low SOC content, due to the climatic conditions [73] caused by high OM mineralization [24], and (iii) land degradation due to intensive management (CT) [94]. In this line, in Mediterranean rainfed OG under CT, there is an interannual decrease of 1.3% of SOC-S in the first 40 cm deep for long-term studies (15 years) that can reach −12.9 Mg C ha^{-1} y^{-1} [83].
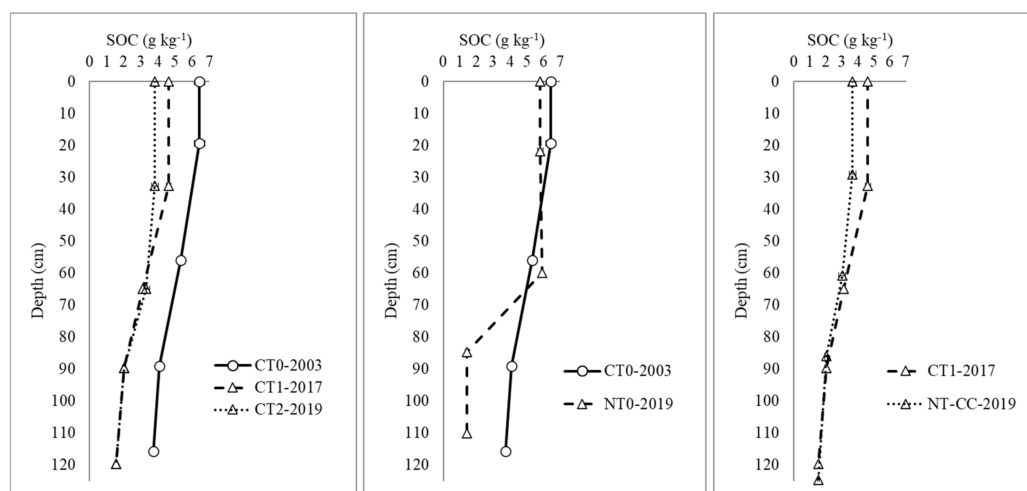

Figure 3. Soil organic carbon distribution in the study area. CT0: conventional tillage 2003, CT1: conventional tillage 2017, CT2: conventional tillage 2019, NT: conventional tillage 2019, NT-CC: no tillage with cover crops.

Usually, the soil quality, as a function of the SR-SOC, was poor (degraded soil) since the SR-SOC values were <2 in absolute values [23,27]. The SR-SOC increased in depth, ranging from 1.21 to 1.73 for SR1-CT0 and SR3-CT0 (Table 5). In this line, in OG soil in CM near the study area, but applying oil mill byproducts to the soil, similar results were

found [95], showing that the addition of residues (pruning remains) can increase the SR index, improve the soil quality, and produce changes in the chemical and physical soil properties [70].

Table 5. Stratification ratio of soil organic carbon and nitrogen (average ± SD) in a Mediterranean olive grove. Initial situation (January 2003), intermediate situation (September 2017), and final situation (September 2019).

Sampling	SR	Horizon Ratio	SR-SOC	SR-TN
January 2003	SR1-CT0	Ap/Bw	1.21 ± 0.24 Aa	1.01 ± 0.10 Aa
	SR2-CT0	Ap/Bw-C	1.58 ± 0.23 Ba	1.07 ± 0.11 Aa
	SR3-CT0	Ap/C	1.73 ± 0.21 Ba	1.21 ± 0.10 Ba
September 2017	SR1-CT1	Ap/Bw	1.48 ± 0.11 Ab	1.31 ± 0.26 Ab
	SR2-CT1	Ap/Bw-C	2.29 ± 0.13 Bb	1.97 ± 0.24 Bb
	SR3-CT1	Ap/C	3.01 ± 0.11 Cb	2.03 ± 0.23 Cb
September 2019	SR1-CT2	Ap/Bw	1.15 ± 0.34 Aa	1.22 ± 0.45 Aa
	SR2-CT2	Ap/Bw-C	1.89 ± 0.23 Bc	1.82 ± 0.38 Bb
	SR3-CT2	Ap/C	2.48 ± 0.26 Cc	1.88 ± 0.26 Bb
September 2019	SR1-NT-CC	Ap/Bw	1.22 ± 0.17 Aa	1.13 ± 0.19 Aa
	SR2-NT-CC	Ap/Bw-C	1.82 ± 0.19 Bc	1.45 ± 0.21 Bc
	SR3-NT-CC	Ap/C	2.39 ± 0.21 Cc	1.46 ± 0.18 Bc
September 2019	SR1-NT	Ap/Bw	0.98 ± 0.17 Ab	1.69 ± 0.23 Ac
	SR2-NT	Ap/Bw-C	4.10 ± 1.43 Bd	1.71 ± 0.31 Ab
	SR3-NT	Ap/C	4.16 ± 1.65 Bd	1.78 ± 0.28 Ab

SD: standard deviation, SR: stratification ratio, SOC: soil organic carbon, TN: total nitrogen. CT0: conventional tillage 2003; CT1: conventional tillage 2017; CT2: conventional tillage 2019; NT-CC1: no tillage with cover crops 2019; NT1: no tillage 2019. Numbers followed by different capital letters in the same column have significant differences ($p < 0.05$) in depths for the same sampling period. Numbers followed by different lowercase letters in the same column have significant differences ($p < 0.05$) between the same horizon in different sampling periods.

It is important to note that, at different depths (SR2-CT0 and SR3-CT0), no significant differences were found ($p < 0.05$) with respect to SR-SOC. This could indicate greater SOC stabilization at depth (SR2-CT0:1.58; SR3-CT0:1.73) than at the surface (SR1:1.21) (Table 5). In this sense, the binding of SOC to fine mineral particles is one of the most important stabilization mechanisms of SOC for mineral soils [96]. This is justified by the high concentrations of fine particles in the soils studied (87.2% and 81.9% for Bw/C and C horizons, respectively) (Table 4). In this sense, it is accepted [97,98] that the greatest SOC content is found in the fine fraction (<20 μ, clay and fine silt) and that SOC is also much more stable in the fine fraction than in the coarse fraction [99]. Based on this premise, the SOC of the studied soils could be stabilized at depth [100] since land use, management, and climatic conditions for more than 50 years (long-time) were stable [21]. Therefore, the SR-SOC is a good indicator of soil quality [23] and an effective technique for monitoring SOC in responses to climate, land use, tillage, and other management effects. In addition, changes in the SR can show changes in the rate of SOC sequestration [101], so high SR-SOC (>2) indicates undisturbed soil and the high soil quality of the surface layer.

In the case of SR-TN, the values were low, ranging from 1.01 (SR1-CT0) to 1.21 (SR2-CT0) (Table 5). In this case, no significant differences were found ($p < 0.05$) superficially (SR1-CT0 and SR2-CT0). TN concentrations were low in all horizons, ranging from 0.93 g kg^{-1} (topsoil) to 0.77 g kg^{-1} (subsoil) (Table 4). Therefore, the N mineralization decreased when the clay content increased; hence, the SR-TN was low [102]. In addition, the aggregate size and clay content affected TN, decreasing N mineralization [55].

3.4. Management Effects on SR-SOC for Medium-Long-Term and Short-Term

The SR-SOC analysis was carried out in the short and medium-term, assuming that for the SOC, long-term stabilization is necessary (> 30 years), since the SOC is conditioned by land use, management, and climatic variables [21], as happens in the preoperational

analysis (period: 1950–2003) (Table 2). Accordingly, from 2003 to the present, different scenarios were studied to analyze the SOC content and the SR-SOC evolution as a soil quality indicator, highlighting:

3.4.1. Medium-Term SR-SOC in Conventional Tillage (from 2003-SR-CT0 to 2017-SR-CT1)

The CT effects (Table 2) on SOC content over 15 years (CT0-2003: CT1-2017) have been very negative, with a SOC loss of between 28% (in surface) and 58% (in depth) (Figure 3). This reduction in the SOC content can be explained by a continuous degradation process due to vegetation loss caused by herbicide use and unsustainable soil management (Table 2). This causes continuous SOM impoverishment, favoring soil erodibility processes and increasing the OM decomposition as a consequence of tillage [74]. In this context, CT contributes to the soil loss due to water erosion [103] and accelerates the OM decomposition due to the breakdown of soil aggregates [104]; furthermore, this process increases with the years of cultivation [105], as we saw with the studied soils. This degradation process has been corroborated in these soils [44], predicting soil losses of 6.6 Mg ha^{-1} yr^{-1} according to the RUSLE model (5% slope) using the quadratic equation ($y = -0.0076x^2 + 1.4042x$; where y = soil loss (Mg ha^{-1} y^{-1}) and x = slope (%)), with high correlation rates ($R^2 = 0.9911$). From these results, we may assume that the soil quality from the SR-SOC due to land management would be lower; however, after 15 years, the management effect (CT0 to CT1) was not negative—on the contrary, the soil quality according to SR-SOC increased, varying by +22.3%, +44.9%, and +73.9% for SR1-CT1, SR2-CT1, and SR3-CT1, respectively (Table 5).

In the case of SR-TN, the trend was similar to SR-SOC, reaching increases of 84.1% (SR2-CT1), with significant differences ($p < 0.05$) for both SR-SOC and SR-TN. In this sense, it is important to note that, at depth, values > 2 (good soil quality) are reached (SR2-CT1-SOC = 2.29; SR3-CT1-SOC = 3.01). However, on the surface, the SR1-CT1-SOC was 1.48 (<2.0). In this sense, lower SR-SOC can be related to less input of OM into the soil [106]. In addition, the SR-SOC < 2 under different land uses may be related to high oxidative conditions [107].

As we can see in Table 5 and Figure 3, SR-SOC increased with soil depth due to the decrease in SOC content along the soil profile. The increase in SR-SOC despite SOC loss from land management (CT) may be due to a process that we can summarize as a high erosion rate due to CT [44] with SOC depletion [104]. As a consequence of this process, the SOC incorporation at depth is reduced, favoring the formation of SOM stable compartments due to the soil aeration by management (removing the soil annually) [108], conditioned by climatic conditions under the olive trees (temperature, shade effect, and differences in the incidence of rain) that produce slower mineralization and more intense humification processes [95], reducing the SOC at depth and increasing the SR-SOC. However, in addition, CT causes a high decomposition of the OC labile fraction by breaking down the macroaggregates [109], together with better soil aeration, increasing the oxygen content and favoring the OM decomposition by microbial activity [110]. Therefore, CT favors aggregate destruction, reducing the OC content of large macroaggregates [111]. In addition, the vegetation and climate determine the SOC vertical distribution along the profile; however, the climate and clay content may be more decisive in the SOC accumulation [112].

3.4.2. Short-Term SR-SOC in Conventional Tillage (2017-SR-CT1 to 2019-SR-CT2)

CT in the short-term between 2017 (TC1) and 2019 (TC2) caused a SOC reduction of -17.5% in the Ap-horizon (CT1:4.63 g kg^{-1}; CT2:3.82 g kg^{-1}) equivalent at 0.40 g kg^{-1} y^{-1}. In the case of the Bw-horizon, there was a slight increase of +6.4% (CT1:3.12 g kg^{-1}; CT2:3.32 g kg^{-1}), equivalent to 0.1 g kg^{-1} y^{-1}; however, at depth, there were no changes (Figure 3).

CT (highly mechanized) (Table 2) in OG cultivation has environmental consequences due to the soil quality loss [101]; this degradation is related to the use of wrong agricultural techniques that lead to continuous soil erosion and rapid SOM depletion [113], favoring a high-risk of water erosion [114] and affecting the physicochemical soil properties [115].

In addition, the $CaCO_3$ loss (parental material: loam and marlaceous lime) in CT due to erosion processes can reduce the soil structure stability, increasing the soil structure degradation [101]. In this sense, Ca^{2+} is the most important cementing agent (for OM and clay) to maintain the soil structure [116], a very relevant issue in the soils studied due to the high Ca^{2+} content [68]. Regarding the SOC increase in the Bw-horizon, it may be due to two mechanisms: first, clayey soils can undergo carbon translocation due to their solubility, soil fauna activity, and the presence of roots [117]; and second, by management (CT), due to the intense tillage mixing the topsoil with the subsurface, which increases the SOC content in the subsurface [118]. However, at depth, there are no changes in the SOC content in the short-term, which could be due to the organic compounds' stabilization by the clays [119].

In two years, the management effects (CT1 to CT2) were negative, producing a reduction in SR-SOC indices of 22.3%, 17.5%, and 17.6%, respectively, for SR1-CT2 SR2-CT2, and SR3-CT2. With respect to the SR-TN, the trend was like that for the SR-SOC (Table 5), producing a loss in soil quality according to the SR-SOC. This behavior—reduction in the SR-SOC by tillage—is normal since if the SOC content is reduced on the surface and the depth remains constant, the SR-SOC decreases. In soils under semiarid conditions and with poor aggregate stability, the SR-SOC could change in the short-term [120,121]. In addition, the CT that characterizes the study soils could exacerbate degradation processes, affecting the soil quality [95] in the following ways: A reduction of soil wettability [122], decreased fertility [123], reduced microbiological-enzymatic activity [34], sorption, persistence, and mobility of herbicides [124], and favoring high soil erosion rates [44].

3.4.3. Land Management Change Effect (CT to NT-CC) in the Short-Term (2017–2019) on SR-SOC

LMC (from CT to NT-CC) in the short-term (two years) had a negative effect on the soil, causing a SOC reduction of -20% and -3.3% for the Ap and Bw-horizons, respectively (Ap: CT1-4.63 g kg^{-1}/Ap: NT-CC-3.67 g kg^{-1}; Bw: CT1-3.12 g kg^{-1}/Bw: NT-CC-3.02 g kg^{-1}); however, there were no changes at depth (Figure 3). Before conducting any analysis, we must consider that, in the short-term, the SOC analysis can offer contradictory results with respect to LMC in semiarid conditions, since climatic variables (low soil moisture and high-temperature) limit the SOC content, delaying the effects of sustainable management practices on SOC content for several years [125]. In this sense, permanent cover use in semiarid environments leads to problems related to competition for water and nutrients between crops, affecting the productivity of the main crop [42]. In our case, we have observed that OG covers did not develop satisfactorily, and the cover also affected the OG production, reducing the average olive production by 40%. This SOC reduction in NT-CC in the short-term due to LMC could be explained by several reasons: first, soil texture and management can affect the SOC content, since soluble organic compounds can leach into deeper horizons, reducing the SOC content superficially [126]; second, this reduction in SOC content could be the result of very intense erosive processes [127] derived from LMC. In this sense, the authors of [43] indicated that NT could negatively affect the soil conservation compared to CT due to a decrease in OM, macroaggregates, and infiltration rates and increased soil consolidation with NT compared to CT in the short-term. In the same way, in the short-term (1–2 years), in semiarid rainfed Mediterranean areas, rainfall is the main limiting factor [128] due to its scarcity and erratic distribution, causing high erosion in agricultural soils during periods of strong storms, also causing high mineralization rates of the SOM due to high temperatures during humid periods, and a lack of residues to cover the soil surface after periods of drought [129], thereby reducing SOC concentrations. Starting from these premises in dry Mediterranean OG and considering the geographical characteristics (low or moderate slope with continuous changes of concavity and convexity), the effect on the SOC using covert is not the desired one, leading to important disagreements about the real impact of the different management options [130,131].

As shown in Table 5, LMC does not cause important changes within two years, and we only saw a slight increase in SR1 (1.15 SR1-CT2; 1.22 SR1-NT-CC). However, LMC affected

SR, producing an SR reduction in all cases (from CT1-2017 to NT-CC-2019). In this sense, it is important to highlight that, although the SR-NT-CC was less than the SR-CT1 when compared with CT2, the SR on the surface improved the soil quality (SR-SOC increased by 9.9%). Therefore, we could assume that a turning point in the soil degradation process was beginning. However, the changes with depth were not significant. The C decomposition rates were lower in deeper horizons than in higher horizons [132]. In addition, SR-SOC, considering deeper horizons in Mediterranean soils, are affected by the C incorporation, as the residues are accumulated in the subsurface horizon [90]. This would suggest that the management system influences soil C accumulation. Furthermore, the supply of OM from the surface to deeper horizons is ensured under NT, which led to an accumulation of C in soils under this system, which will affect the SR-SOC.

3.4.4. Land Management Change Effects (from CT0 to NT) on SR-SOC for the Medium to Long Term (2003–2019)

The LMC from CT0 to NT in the medium-long-term (2003–2019) showed variations in the SOC content of −9.6%, +11.3%, −65.2%, and −61.8% for the Ap, Bw, Bw/C, and C horizons, respectively (Ap: CT0 6.44 g kg^{-1}/Ap: NT 5.82 g kg^{-1}; Bw: CT0 5.32 g kg^{-1}/Bw: NT 5.94 g kg^{-1}; Bw/C: CT0 4.08 g kg^{-1}/Bw/C: NT 1.42 g kg^{-1}; C: CT0 3.73 g kg^{-1}/C: NT 1.42 g kg^{-1}) (Figure 3), with significant differences ($p < 0.05$) in all horizons in relation to management.

Regarding the SOC reduction after the LMC, although most studies in semiarid areas in Spain show SOC increases at the surface [133,134], our results were the opposite, with a SOC reduction in the topsoil (−9.6%). This reduction in the SOC content in the study area may be due to the absence of vegetation cover due to herbicide application (Table 2) and the maintenance of bare soil. In this sense, vegetation cover absence and the long-term maintenance of bare soil due to herbicide use cause a crust formation and accelerates the erosion processes, reducing the SOC content in rainfed OG [18]. In addition, this process can be accelerated by periods of intense rainfall [128]. However, LMC produced an increase of +11.3% in the SOC content in the Bw-horizon. Similar results have been obtained by other authors [126], indicating that soil texture and land management can affect the SOC dynamics, which can be reduced on the surface and increased in deeper layers due to the organic compounds' solubility. At depth, the SOC contents were drastically reduced (−65.2%: Bw/C-horizon and −61.8% C-horizon) with respect to CT0. Hence, the SOC content at depth depends on the superficial SOC since OM contributions are received in the form of fine roots, root exudates, and dissolved OC [93]. Given these results, it is important to note that, at depth, all the scenarios show very similar values for SOC content, regardless of the management used (CT, NT-CC, and NT); therefore, we can assume that the SOC stabilization mechanisms associated with the soil fine fraction at depth were taking place [96]. These results are corroborated by other researchers [55], who found that the aggregates' stability increases along with a decrease in the total SOC-S associated with the aggregate fractions and an increase in the percentage of SOC-S in the macroaggregate fractions at depth, indicating the importance of studying the soil in-depth and not only superficially (topsoil).

The SR-SOC was highly variable, ranging between 0.98 (SR1-NT) and 4.16 (SR3-NT), although in both cases (CT0 and NT), the SR-SOC decreased in depth. LMC from CT0 to NT for 17 years caused significant differences ($p < 0.05$) in the SR-SOC at the surface and at depth, being more important at depth than at the surface (Table 5). On the surface (SR1), the LMC caused a loss of soil quality, reducing the SR by 19% (from 1.21 SR1-CT0 to 0.98 SR1-NT); however, at depth, the SR-SOC increased by 140.5% (from 1.73 SR3-CT0 to 4.16 SR3-NT1), improving the soil quality.

The SR-SOC increased at depth due to LMC in NT. This may be due to several continuous processes over time: (i) a first stage produced a SOC reduction due to the herbicide application and the OM reduction, favoring water erosion processes and therefore, a continuous SOC loss on the surface [18]; (ii) second, there is a SOC loss and intense microbial decomposition due to climatic factors, so high temperatures can affect the microorganisms'

activity, accelerating the SOC decomposition [135] and affecting to SOC content at depth; and (iii) in a third stage where the SOC remains stabilized, linked to the fine fraction (<20 μ, clay and fine silt) [99], the SOC of the studied soils could be stabilized at depth [100], as we can observe for all the management processes studied. Although there was a SOC reduction in NT, the factors mentioned above cause an increase in the SR-SOC (SR > 2); therefore, they increased the soil quality with respect to other management. It is important to highlight that it would be necessary to carry out studies of the soil's physical properties to provide more information on this matter.

3.5. Influence of Topographic Position in Land Management Change (from CT1 to NT-CC) on SR-SOC for the Short Term (2017–2019)

The analysis of SOC content in all the studied situations (managements and hillside positions) showed three important characteristics: (i) low SOC concentrations due to climatic conditions [73], (ii) a SOC reduction at depth due to high OM mineralization and the lack of crop residues after dry periods [24], which affects the SOC content at depth [18], and (iii) an increase of SOC content as we descend along the hillside due to degradation process associated with water erosion processes [44] in the highest topographic positions and soil accumulation processes in the hillside's lower parts [18] (Figure 4). These factors, acting synergistically, can cause decarbonization processes in the soil [56].
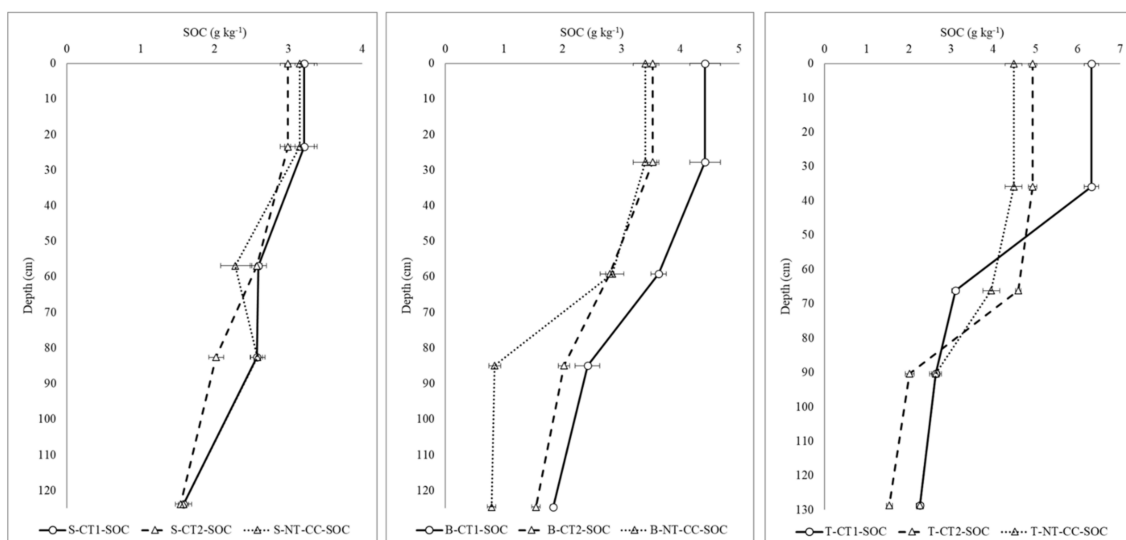

Figure 4. Soil organic carbon content in the hillside position. Conventional tillage and no tillage with cover crops. S: summit, B: backslope, T: toeslope; CT1: conventional tillage 2017, CT2: conventional tillage 2019, NT-CC: no tillage with cover crops.

A detailed analysis regarding the OM, SOC, and SOC-S distribution of these soils has been carried out [18,83], concluding that LMC from CT1 to NT-CC for the short-term (two years) had a positive effect on SOC in S and T position; however, in the B position, this effect was negative. LMC caused a SOC reduction in the Ap horizon and an increase in the Bw horizon due to slight textural changes (clay content), and the soluble organic compounds' presence can be filtered by depth; in addition, the SOC concentrations due to LMC from CT1 to NT-CC in the short-term caused carbonization (position S and T) and decarbonization (position B) of the soil.

The topographic position effect to SR-SOC showed that the SR-SOC was highly variable (Table 6), ranging between 1.07 and 4.30 for the CT2 Ap/Bw T-position and NT-CC Ap/C B-position, respectively. Despite this variability, we can say that the S topographic position had the lowest SR-SOC values, being higher in the two remaining topographic positions (T and S). One of the important features was that the SR-SOC increased with depth, except for the CT1 B-position, which decreased with depth (CT1: sR1:2.51, SR2:1.88

and SR3:1.87). Another very important issue to highlight was that, on the surface (SR1), the SR-SOC in all situations was <2, except for the CT1 Ap/Bw backslope (SR1:2.51) (Table 6).

The starting point CT1 (2017) showed a preferential increase of the SR-SOC as we went down along the hillside and, therefore, the highest values were found in T-position. Likewise, we can affirm that the highest soil quality as a function of the SR-SOC was in the hillside's lower parts (T-position), ranging from 1.66 (SR1) to 2.87 (SR3) in CT1 (Table 6). This increase in SR-SOC along the hillside in the lower parts could be due to water erosion processes. In this sense, the SR-SOC reduction superficially (Ap-horizon) could be due to soil erosion [136], so that CT with intensive tillage contributes to soil loss [103] due to water erosion accelerating the OM decomposition rates and causing structural aggregates' degradation in topsoil, thereby increasing the SR-SOC at depth [137].

Table 6. Stratification ratio of soil organic carbon (average ± SD) in a Mediterranean olive grove. Initial situation (September 2017) and final situation (September 2019) in three topographic positions (toeslope, backslope, and summit) with two types of management (conventional tillage or no-tillage with cover crops).

		Sampling		
		2017	2019	
		CT1	CT2	NT-CC
Topographic Position	Horizon Ratio	SR-SOC	SR-SOC	SR-SOC
Toeslope	Ap/Bw	1.66 ± 0.14 Aa	1.07 ± 0.10 Ab	1.13 ± 0.06 Ab
	Ap/Bw-C	2.86 ± 0.11 Ba	2.44 ± 0.16 Bb	1.71 ± 0.11 Bc
	Ap/C	2.87 ± 0.13 Ba	3.20 ± 0.13 Cb	1.98 ± 0.15 Cc
Backslope	Ap/Bw	2.51 ± 0.09 Aa	1.26 ± 0.09 Ab	1.20 ± 0.10 Ab
	Ap/Bw-C	1.88 ± 0.19 Ba	1.75 ± 0.18 Ba	4.05 ± 0.12 Bb
	Ap/C	1.87 ± 0.07 Ba	2.29 ± 0.13 Cb	4.30 ± 0.14 Cc
Summit	Ap/Bw	1.17 ± 0.12 Aa	1.16 ± 0.11 Aa	1.38 ± 0.09 Ab
	Ap/Bw-C	1.24 ± 0.16 Aa	1.48 ± 0.13 Bb	1.22 ± 0.11 Aa
	Ap/C	2.03 ± 0.09 Ba	1.94 ± 0.08 Ca	1.99 ± 0.13 Ba

SD: standard deviation, SR: stratification ratio, SOC: soil organic carbon. CT1: conventional tillage 2017; CT2: conventional tillage 2019; NT-CC1: no tillage with cover crops 2019. Numbers followed by different capital letters in the same column have significant differences ($p < 0.05$) in depth for the same sampling period. Numbers followed by different lowercase letters in the same column show significant differences ($p < 0.05$) between the same horizon in different sampling periods.

Regarding the final situation (CT2), a clear and defined trend was not observed, but a slight increase in the SR-SOC could be seen at depth, and a slight reduction in the SR at the surface, except for the S position where this relationship was reversed. Some authors [138] have pointed out that the SR-SOC is favored by large soil OM inputs, high soil clay content, and a saturated soil calcium matrix. However, this phenomenon could be explained by soil management and texture since the SR-SOC can be reduced in the soil surface due to soluble organic compounds that can filter into the soil at depth, increasing the soil aggregates [126].

However, the LMC from CT1 to NT-CC for two years (short-term) causes two very important effects. First, there is a soil loss quality in the T position, with an SR-SOC reduction that could reach −40% in SR2 NT-CC. NT can negatively affect the soil quality compared to CT [43] due to infiltration rates, macroaggregates, OM decrease, and an increase in soil compaction and consolidation with NT compared to CT in the short-term. This reduction could be the result of very intense erosive processes [127] derived from LMC.

Second, an opposite effect we can observe is an SR-SOC increase in the B position, which can reach up to +130%, with SR-SOC values of 4.30 (SR3-NT-CC). In the case of

the S position, no changes were observed due to the LMC. In this sense, in CM, similar results were obtained in the toposequences of traditional OG [139], indicating an increase in SOM and fine particles on hillsides due to water erosion. Other researchers [136] have highlighted the contribution, especially in semiarid areas, of the erosion process to SR-SOC loss. The absence of tillage in NT improves the formation of stable aggregates and the microbial and fauna communities of the soil [140], which provides protection against OM decomposition [141]. In the case of the S position, no changes were observed due to the LMC.

4. Conclusions

The main conclusions emerging from this research are: (i) CT (strongly mechanized) in rainfed OG over time (from CT-1950 to CT0-2003: long-term) under semiarid conditions leads land degradation processes, low SR-SOC (1.21–1.73: poor soil quality) and low capacity for agricultural use, inducing soil decarbonization by erosion processes, (ii) CT over time (from CT0-2003 to CT1-2017: medium long-term) involved a SOC reduction, however, the SR-SOC increased (2.29 and 3.01: good soil quality) due tillage, affecting to less OM input into the soil, accelerating the erosion processes, favoring the formation of SOM stable compartments by soil aeration, reducing the SOC at depth and increasing the SR-SOC, (iii) CT in the short-term (from CT1-2017 to CT2-2019) caused a SOC reduction in topsoil and slight increases in sub soil, with a SR-SOC reduction (loss of soil quality) due to wrong agricultural management techniques (if the SOC content is reduced at the surface and the concentrations at depth remain constant, the SR-SOC decreases), (iv) LMC in the short-term (from CT1-2017 to NT-CC-2019) caused a SOC reduction (−20% and −3.3% for the Ap and Bw-horizon, respectively; unchanged at depth) due to low soil moisture and high-temperature, increasing in surface the SR-SOC (+9.9%), so a turning point in the soil degradation process may be beginning, (v) LUC in the medium long-term (from CT0-2003 to NT-2019) showed variations in the SOC content (−9.6%, +11.3%, −65.2%, and −61.8% for the Ap, Bw, Bw/C, and C horizons, respectively), causing a loss of soil quality in topsoil (SR −19%) and an increase in depth (SR +140.5%) improving the soil quality, this increase was due to a SOC reduction by herbicide application, favoring water erosion processes with SOC loss on surface, a SOC loss due to intense microbial decomposition due to the climate factors, and by SOC stabilized processes linked to the fine fraction, and (vi) the hillside position also affected the LMC (from CT1-2017 to NT-CC-2019: short-term), so that the SOC content increased as we descended along the hillside due to erosion with soil accumulation processes in the hillside's lower parts, LMC produced a soil loss quality in the T position (SR-SOC: −40% in SR2 NT-CC) due to SOM decreasing by soil compaction and consolidation with intense erosive processes derived from LMC, in the case of the B position, the SR-SOC increased (+130%: sR3-NT-CC, 4.30) due to NT-CC improve the formation of stable aggregates and the microbial and fauna communities of the soil, which provide protection against OM decomposition, in the case of the S position no changes were observed due to the LMC.

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