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Short and Long-Term Effect of Land Use and Management on Soil Organic Carbon Stock in Semi-Desert Areas of North Africa-Tunisia

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Abstract: Soil organic carbon (SOC) plays an important role in the global C cycle, as well as in the maintenance and improvement of the soil quality. Over time, special attention has been paid to it in the study of the SOC reserves worldwide; however, reduced attention has been given to assessing the spatial patterns of SOC stock (SOCS) in semi-desert ecosystems. In this line, there are no conclusive studies in drylands of Africa affected by aeolian processes (semi-desert conditions) mainly due to the complexity of sample collection, and this is especially significant in some soil types such as Arenosols (AR) and Calcisols (CL). This study evaluated the spatial variability of SOC and SOCS in AR and CL with woody crops in relation to land use and management (old plantations > 100 years: centenary olive grove; new plantations < 12 years: young olive grove, almond, and pistachio) in semi-desert conditions. For this purpose, 16 soil profiles (for 0–40 and 40–100 cm depth) were selected and studied in an experimental area of Menzel Chaker-Sfax in southeastern Tunisia (North Africa). The main results indicated that the SOCS on average was higher in Old Cultivated AR (OC-AR) with 41.16 Mg ha^{-1} compared to Newly Cultivated AR (NC-AR) with 25.13 Mg ha^{-1}. However, the SOCS decreased after a long period of cultivation in CL from 43.00 Mg ha^{-1} (Newly Cultivated CL: NC-CL) to 32.19 Mg ha^{-1} (Old Cultivated CL: OC-CL). This indicates that in the long term, CL has more capacity to store SOC than AR, and that in the short term, AR is more sensitive to land management than CL.

Keywords: arid climate; land use; land management; Calcisols; Arenosols; soil organic carbon stocks; olive grove; almond grove; pistachio grove

1. Introduction

In most terrestrial ecosystems, soil organic carbon (SOC) is the largest carbon (C) pool [1] containing approximately 2344 Gt of organic C globally [2]. In fact, SOC is an essential element of earthly life and constitutes the most fertilizing element of the soil, and SOC content is an important indicator of biological and microbiological activity [3,4]. Therefore, SOC and soil organic matter (SOM) are considered major factors that influence the soil quality, affecting agricultural productivity, soil structural stabilization, plant nutrients retention, and water-holding capacity, among other things [5,6]. However, in addition, SOC stock (SOCS) depends on factors such as wildlife, earthworms, ants, and microorganisms such as fungi and bacteria and organic waste [7], and this SOCS can be found at 0–2 m depth [8,9]. Other factors that can affect to SOCS are the climatic conditions (precipitation and temperature) and agriculture practices (land use and management) [10]. In this sense, high temperatures, low rainfall, and intensified tillage can accelerate SOM decomposition, conditioning agricultural production in many regions of the world [11]. Therefore, a decrease in the SOM content leads to reduction in soil fertility and productivity [12]. Therefore, SOCS should be estimated to evaluate the impact of land management practices on soil fertility and in the greenhouse gases generation [13,14].

All these considerations are especially important in drylands (semi-arid, arid, semi-desert, and desert areas) with low average annual rainfall (<500 mm) [15], with a cover more than one-third of the Earth's land surface, and with more than 36% of the world's SOCS [16,17]. In this line, [18] indicates that these ecosystems can be more responsive to elevated CO_2 than others because net primary productivity is mostly limited by water availability. Additionally, other authors such as [19] have reported that desert soils exhibit higher atmospheric CO_2 fixation capacity than other soils (e.g., meadow soils).

In this sense, researchers in [20] indicated that dryland areas in Tunisia is characterized by low SOCS (18.7 Mg ha^{-1}) due to sandy texture, which is associated with low SOM content and reduced cation exchange capacity [21,22], highlighting that in sandy soils, the SOM decomposition has a higher rate than in soils with high clay content [23]. However, water scarcity is also considered as another crucial factor that causes soil degradation, and a decrease in SOC content in semi-arid and arid regions [24]. On average, every year, arid areas have long drought periods (4 to 6 months), so the generation of natural biomass as C source is limited by climatic conditions, but this problem is maximized due to management practices in these arid regions, since the highly intensified tillage causes a loss of spontaneous vegetation cover [25]. The main consequence of these processes acting synergistically is that these soils are highly vulnerable to degradation processes, due mainly to SOM depletion and wind erosion, which cause desertification, which is intensified by the current global warming crisis [26,27].

Recently, many researchers have shown great interest in the SOCS prediction (at regional scale), extrapolating the SOCS on a wide range of soil and/or vegetation types in arid areas of Africa [20]. In this line, [28] analyzed the SOC storage evolution in relation with tillage system in three soil types (Vertisols, Cambisols, and Luvisols) under Mediterranean climate, emphasizing that the SOC was significantly higher in no tillage compared to conventional tillage (10% more in Vertisols and 8% more in Cambisols), with no significant differences in the Luvisols case. More recently, [29] studied the SOCS distribution in Cambisols under different crops in semi-arid Tunisian climate, suggesting that the SOCS has exceeded the national and international standards in Cambisols. Additionally, in Tunisia, SOCS was assessed in different soil types including Lithosols, Solonochaks, Cambisols, and Regosols [20,29,30]; however, Calcisols (CL) and Arenosols (AR) have not been studied yet. In this line, is important to note that three quarters of Tunisia is under arid or semi-desert climate. Therefore, analyzing the SOCS in CL and AR in Tunisian is important to improve the soil quality and its productive capacity, in addition to being able to extrapolate these data to other semi-desert areas to intervene in the land use and management of these soil types. In this sense, several studies have established that soils in arid and semi-desert regions after cultivation suffer significant variations in their biological, physical, and chemical properties [31–35]. However, little research has focused on assessing the effects of woody crops (olive, almond, and pistachio) at different development stages in AR and CL during short- and long-term periods and their relationship with the soil properties and

SOCS. Therefore, due to the role that these soils play in C sequestration and in the crop productivity, it is essential to understand the effectiveness of land use and managements under extreme climatic conditions not only in terms of physical properties but also in the C dynamic variation.

Given this scenario, the general objectives of this study are *(i)* to study the SOC in Calcisols and Arenosols of Tunisia (dryland rainfed area) and *(ii)* to analyze in the short and long terms the soil's capacity for SOC stock under different land uses and management.

2. Materials and Methods

2.1. Study Area

The study area is in an experimental farm of Essalema, located at 50 km in the north-west in Sfax governorship, in the Menzel Chaker delegation—Tunisia (34°59′15′′ N–10°20′03′′ W) (Figure 1). This area covers a surface of 18,670 ha and is divided into seven sub-farms, with an average altitude of 161 m.a.s.l., ranging from 105 m.a.s.l. to 217 m.a.s.l. (meters above sea level), with slopes < 3% slightly undulating.

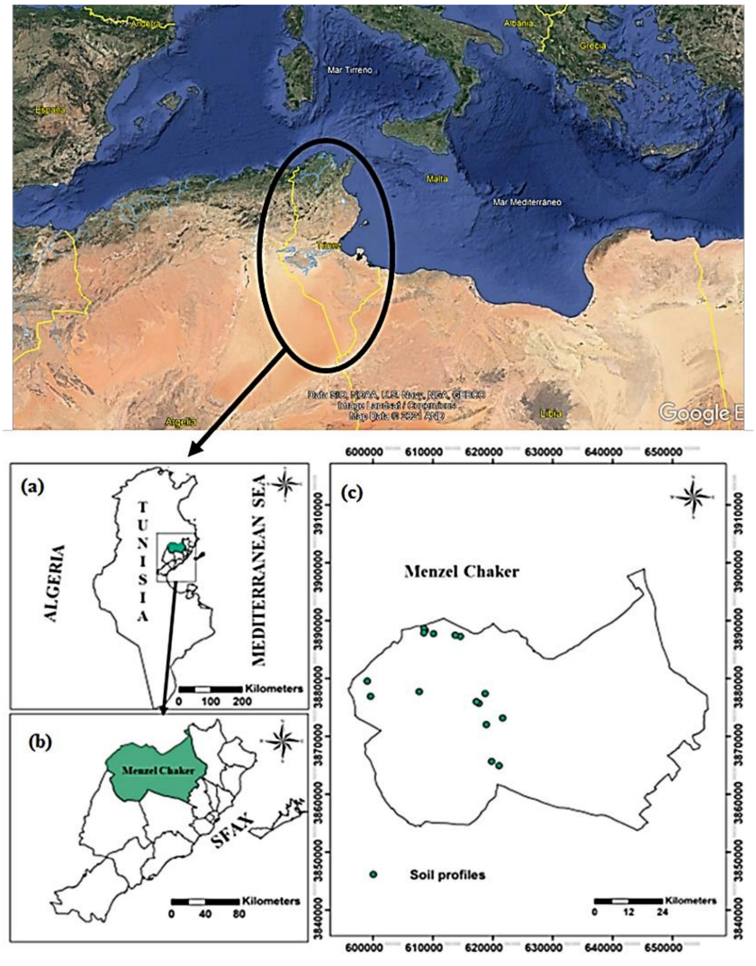

Figure 1. Maps of the study area: (**a**) Tunisia map, (**b**) Sfax location, and (**c**) Menzel-Chaker district with the location of soil profiles https://earth.google.com/web/@36.6638314,7.9704552,553.33197981a,3949044.97759938d,35y,0h,0t,0r (Google Earth Pro—Access: 27 September 2021).

The climate is arid Mediterranean and hot arid steppe according to the Köppen–Geiger updated classification [36]. The annual average temperature was 19.5 °C, with a maximum air temperature of 33 °C in August and a minimum air temperature of 6 °C in January (temperature data provided by the National Institute of Metrology for the period 1966–2019). The annual average precipitation was 169 mm and monthly rainfall ranges from 6 mm (July) to 34 mm (October) (rainfall data provided by Salama farm station for the period 2008–2019).

The study area is characterized by outcrops of the Middle and Upper Continental Pleistocene, and the Lower Pleistocene, formed by limnic sabkhas (deposits of coastal flats subject to periodic flooding and evaporation) and recent alluvium. Most of the wadis are endorheic, leading to closed depressions of the Sebkhas and Garâas type. Depending on their morpho-structural conditions, these closed depressions take the form of synclinal basins (Menzel Chaker region) or the form of Sebkha sand Garâas (Bou Jmal, Karafita). In the dryland regions, the aeolian processes also play an important role, particularly where the precipitation is lows (<150 mm y^{-1}) [37,38], so the aeolian materials accumulation leads to the poorly developed sandy soils formation [39], as it happens in the study area's experimental field [40].

2.2. Soil Sampling and Analytical Methods

Samples from 16 soil profiles were collected: 10 in CL and 6 in AR (these soil types covered most of the studied area ~70%). All investigated soils were tilled to depths varying between 20 and 30 cm (can reach up to 40 cm deep) four to six times per year using a tractor with cultivator depending on rainfall. Soil profiles were dug with a mini excavator, and soil samples were collected at different soil control section for each soil profile (S1: 0–40 cm; S2: 40–100 cm), for a proper determination of physical and chemical soil properties [41,42].

The collected samples were labeled (A1–A5: samples of the Newly Cultivated Calcisols (tilled < 12 years)—NC-CL; M1–M5: samples of the Old Cultivated Calcisols (tilled > 100 years)—OC-CL; C1–C3: samples of the Newly Cultivated Arenosols (tilled < 12 years)—NC-AR; B1–B3: samples of the Old Cultivated Arenosols (tilled > 100 years)—OC-AR).

Soil samples were placed in polyethylene bags, which were labeled and transferred to the laboratory and air dried. Once dried, the samples were sieved at 2000 µm, 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 1, according to handbook of plant and soil analysis for agricultural systems [43]. Soils were described and classified according to World Reference Base for Soil Resources [38].

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

Parameters	Method
Field measurements	
Bulk density (Mg m^{-3})	Core method [44] [a]
Laboratory analysis	
Particle size distribution	Robinson pipette method [45] [b]
pH—H_2O	Suspension in water 1:2.5 [46]
Total Organic C (g kg^{-1})	Walkley and Black method [47]
$CaCO_3$ (%)	Soil Calcium carbonate equivalent [48,49]
Parameters calculated	
SOC-S (Mg ha^{-1})	SOC-S = SOC concentration × BD × d × (1 − δ2 mm%) × 10^{-1} [50–52] [c]
T-SOC-S (Mg ha^{-1})	T-SOC-S = $\Sigma_{\text{soil horizon } 1 \ldots n}$ SOC-S $_{\text{soil horizons}}$ [52] [d]

For all the parameters studied, the recommendations of the Handbook of Plant and Soil Analysis for Agricultural Systems have been followed [43]. [a] 3 cm in diameter, 10 cm in length, and 70.65 cm^3 in volume. [b] Prior to determination of particle size distribution, samples were treated with H_2O_2 (6%) to remove organic matter (OM). Particles larger than 2 mm were determined by wet sieving, and smaller particles were classified according to USDA standards (2004). [c] Where SOC is the organic carbon content (g kg^{-1}), d is the thickness of the soil layer (cm), δ2mm is the fractional percentage (%) of soil mineral particles >2 mm in size in the soil, and BD is the soil bulk density (Mg m^{-3}). [d] T-SOC-S: Total SOC stock determined by adding all the soil horizons considered.

2.3. Experimental Design

The research was carried out in an experimental farm in Essalema–Sfax–Menzel–Tunisia. For this, two soil types were selected (AR and CL), with different land uses (OG: olive grove, AT: almond and PT: pistachio) and managements. The soils' evolution in the short (<12 years) and long terms (>100 years) was compared to analyze the effects of management on SOCS. Land use and management are characterized in Tables 2 and 3 and Figure 2.

Table 2. Land use, managements, and soil qualifiers of the soils (Arenosols) in the study area.

Soil		SP	Soil Type	Hor	Depth (cm)	Land Use	Management
AR	OC-AR	B1	ARca	Ap AC	0–40 40–100	OG	Density: 17 trees ha^{-1}; Amendments: sheep manure mixture; Olive pomace 3.5 Mg ha^{-1} every 10 years
		B2	ARca	Ap C	0–40 40–100	OG	Density: 20 trees ha^{-1}; Amendments: Olive pomace 3.5 Mg ha^{-1} every 10 years
		B3	AReu	Ap AC	0–40 40–100	OG	Density: 17 trees ha^{-1}; Amendments: sheep manure mixture; Olive pomace 3.5 Mg ha^{-1} every 10 years
	NC-AR	C1	ARca	Ap C	0–40 40–100	AT	Density: 68 trees ha^{-1}; The plowing is Canadian type (plowing just with the tails of the washers). Without organic amendment
		C2	ARca	Ap BC	0–40 40–100	OG	Density: 34 trees ha^{-1}; Without organic amendment
		C3	AReu	Ap C	0–40 40–100	OG	Density: 34 trees ha^{-1}; Without organic amendment

ARca: Calcaric Arenosols; AReu: Eutric Arenosols; SP: Soil profile; OC-AR: Old cultivated (tilled > 100 years) Arenosols; NCAR: Newly cultivated (tilled < 12 years) Arenosols; SP: Soil Sampling; Hor: Horizon; OG: Olive grove; AT: Almond tree. C2 and C3: The plowing is Canadian type (plowing just with the tails of the washers when the OG is big, sometimes using the blade types. They are plowed 4 times/year.

Table 3. Land use, managements, and soil qualifiers of the soils (Calcisols) in the study area.

Soil	M	SP	Soil Type	Hor	Depth (cm)	Land Use	Management
CL	OC-CL	M1	ha CL	Ap 2Ck	0–40 40–100	OG	Density: 20 trees ha^{-1}; Amendments: sheep manure mixture 3.5 Mg ha^{-1} every 10 years
		M2	ha CL	Ap 2Bk	0–40 40–100	OG	Density: 17 trees ha^{-1}; Amendments: sheep manure mixture; Olive pomace 3.5 Mg ha^{-1} every 10 years
		M3	ha CL	Ap Ck	0–40 40–100	OG	Density: 17 trees ha^{-1}; No Amendments
		M4	ha CL	Apk 2Ck	0–40 40–100	OG	Density: 17 trees ha^{-1}; No Amendments
		M5	ha CL	Ap 2Ck	0–40 40–100	OG	Density: 17 trees ha^{-1}; No Amendments
	NC-CL	A1	ha CL	Ap 2Ck	0–40 40–100	OG	Density: 34 trees ha^{-1}; Amendments: sheep manure mixture 1 Mg ha^{-1} every 10 years
		A2	ha CL	Ap Ck	0–40 40–100	OG	Density: 34 trees ha^{-1}; Amendments: sheep manure mixture 1 Mg ha^{-1} every 10 years
		A3	ha CL	Ap 2Ck	0–40 40–100	OG	Density: 34 trees ha^{-1}; Amendments: sheep manure mixture 1 Mg ha^{-1} every 10 years
		A4	ha CL	Ap Ck	0–40 40–100	AT	Density: 68 trees ha^{-1}; The plowing is Canadian type (plowing just with the tails of the washers)
		A5	ha CL	Ap 2Bk	0–40 40–100	PT	Density: 39 trees ha^{-1}; The plowing is Canadian type (plowing just with the tails of the washers)

ha CL: Haplic Calcisols; OC-CL: Old cultivated (tilled > 100 years) Calcisols; M: Management; SP: Soil Profile; NC-CL: Newly cultivated (tilled < 12 years) Calcisols; SP: Soil Sampling; Hor: Horizon; OG: Olive grove; AT: Almond tree; PT: Pistachio tree. A1, A2, and A3: The plowing is Canadian type (plowing just with the tails of the washers when the OG will be big, they use sometimes the blade types. They are plowed 4 times/year. M1, M2, M3, M4, and M5: The plowing is of the Canadian type. In the fall, they use the tails of the two-row pucks, in the winter they use the blade (teeth), one row only, and in the spring, they use the tails of the pucks (two rows) for weeding. During the summer, they use the blade (teeth), a single row.

Figure 2. Different land uses in the experimental farm: Centenary olive grove, young olive grove, almond tree, and pistachio tree. (**1**): Centenary olive grove—old cultivated > 100 years; (**2**): young olive grove—newly cultivated < 12 years; (**3**): almond tree—newly cultivated < 12 years; (**4**): pistachio tree—newly cultivated < 12 years.

All soil samples were taken at the same time (synchronic approach) under different management practices at known durations from an initial reference state, and the SOCS was compared under this initial reference state [53].

2.4. Statistical Analyses

The effect of land management and soil depth on soil properties was analyzed using SPSS 20.0 for Windows. Data were tested for normality to verify the model assumptions using Duncan's multiple range tests, and differences of $p < 0.05$ were considered statistically significant.

3. Results and Discussion

3.1. Soil Characterization

The soils studied are developed from loamy or sandy material often of aeolian origin, and all soils had simple morphology with two genetic horizons—Ap horizon and underlying horizons with calcium carbonates accumulation (Ck and Bk); according to [38], the studied soils were mainly Haplic CL (CLha), Calcaric AR (ARca) and Eutric AR (AReu) (Tables 2–5).

Table 4. Principal soil properties evaluated (average ± SD *) in the soil profile by soil control section in Arenosols.

Soil	M	SP	LU	Hor	Depth (cm)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	BD (Mg m^{-3})	pH (H_2O)	$CaCO_3$ (%)	OC (%)
AR	OC-AR *n* = (3 × 2)	B1	OG	Ap	0–40	1.15	96.37	1.17	2.46	1.701	9.18	2.64	0.125
				AC	40–100	0.60	92.99	4.62	2.39	1.645	9.14	2.78	0.330
		B2	OG	Ap	0–40	1.91	94.66	1.69	3.65	1.692	9.25	4.06	0.290
				C	40–100	6.74	92.95	2.44	4.61	1.673	9.19	7.42	0.171
		B3	OG	Ap	0–40	1.48	98.22	0.34	1.44	1.705	9.09	0.51	0.282
				AC	40–100	2.60	98.05	0.49	1.46	1.681	9.10	0.55	0.290
		X		Ap	0–40	1.51 ± 0.28	96.42 ± 1.78	1.07 ± 0.68	2.52 ± 1.11	1.70 ± 0.01	9.17 ± 0.08	2.40 ± 1.79	0.23 ± 0.09
				AC	40–100	3.31 ± 3.13	94.66 ± 2.93	2.52 ± 2.07	2.82 ± 1.62	1.67 ± 0.02	9.14 ± 0.05	3.58 ± 3.51	0.26 ± 0.08
	NC-AR *n* = (3 × 2)	C1	AT	Ap	0–40	2.98	80.51	10.75	8.74	1.560	8.95	4.11	0.270
				C	40–100	4,32	82.58	8.38	9.04	1.530	8.94	6.49	0.165
		C2	OG	Ap	0–40	0.66	88.91	5.22	5.87	1.632	8.81	3.03	0.290
				BC	40–100	0.88	95.32	1.33	3.35	1.681	8.68	2.63	0.095
		C3	OG	Ap	0–40	0.09	94.01	2.23	3.76	1.670	9.12	1.04	0.145
				C	40–100	0.44	91.58	2.09	6.33	1.690	9.17	0.81	0.065
		X		Ap	0–40	1.24 ± 1.53	87.81 ± 6.82	6.07 ± 4.32	6.12 ± 2.50	1.62 ± 0.06	8.96 ± 0.16	2.73 ± 1.56	0.24 ± 0.08
				C	40–100	1.88 ± 2.13	89.83 ± 6.55	3.93 ± 3.87	6.24 ± 2.85	1.63 ± 0.09	8.93 ± 0.25	3.31 ± 2.90	0.11 ± 0.05

SD *: Standard deviation; M: Management; SP: Soil sampling; Hor: Horizon; BD: Bulk density; OC: Organic carbon; *n* = Sample size. OC-AR: Old cultivated (tilled > 100 years) Arenosols; NC-AR: Newly cultivated (tilled < 12 years) Arenosols.

Table 5. Principal soil properties evaluated (average ± SD *) in the soil profile by soil control section in Calcisol.

Soil	M	SP	LU	Hor	Depth (cm)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	BD (Mg m^{-3})	pH (H_2O)	$CaCO_3$ (%)	OC (%)
CL	OC-CL *n* = (3 × 2)	M1	OG	Ap	0–40	6.91	91.43	3.77	4.80	1.621	9.26	5.66	0.131
				2Ck	40–100	7.47	74.28	8.69	17.03	1.591	9.10	20.47	0.201
		M2	OG	Ap	0–40	0.81	92.14	2.85	5.01	1.610	9.19	4.27	0.260
				2Bk	40–100	2.38	56.41	21.17	22.42	1.342	8.81	22.03	0.295
		M3	OG	Ap	0–40	23.54	73.98	12.89	13.13	1.330	8,78	11.61	0.540
				Ck	40–100	41.86	63.59	14.45	21.96	1.451	8.99	21.97	0.230
		M4	OG	Apk	0–40	16.16	90.97	5.79	3.24	1.570	9.12	10.08	0.115
				2Ck	40–100	6.20	63.32	3.94	32.74	1.501	8.74	54.48	0.255
		M5	OG	Ap	0–40	0.73	91.03	6.31	2.66	1.531	9.29	1.99	0.215
				2Ck	40–100	2.28	66.14	31.16	2.70	1.420	9.19	21.94	0.255
		X		Ap	0–40	9.63 ± 10.00	87.91 ± 7.80	6.32 ± 3.94	5.77 ± 4.24	1.53 ± 0.12	9.13 ± 0.21	6.72 ± 4.02	0.25 ± 0.17
				2Bk/Ck	40–100	12.04 ± 16.83	64.75 ± 6.44	15.88 ± 10.70	19.37 ± 10.93	1.46 ± 0.09	8.97 ± 0.19	28.18 ± 14.72	0.25 ± 0.04
	NC-CL *n* = (3×2)	A1	OG	Ap	0–40	1.56	82.93	9.08	7.99	1.570	8.77	9.34	0.271
				2Ck	40–100	3.80	61.04	16.72	22.24	1.351	8.74	26.16	0.285
		A2	OG	Ap	0–40	4.28	78.68	8.76	12.56	1.541	8.72	7.80	0.351
				Ck	40–100	0.64	60.01	22.25	17.74	1.355	8.74	22.76	0.265
		A3	OG	Ap	0–40	10.85	69.64	12.85	17.51	1.412	8.95	17.13	0.395
				2Ck	40–100	21.60	51.58	18.83	29.59	1.371	8.83	35.41	0.402
		A4	AT	Ap	0–40	14.47	53.30	25.64	21.06	1.032	8.90	19.41	0.490
				Ck	40–100	9.83	65.53	14.81	19.66	1.461	8.93	21.26	0.271
		A5	PT	Ap	0–40	3.24	77.06	13.75	9.19	1.370	8.83	9.80	0.560
				2Bk	40–100	11.99	54.22	18.71	27.07	1.355	8.87	32.37	0.275
		X		Ap	0–40	6.88 ± 5.51	72.32 ± 11.67	14.02 ± 6.87	13.66 ± 5.54	1.39 ± 0.22	8.83 ± 0.09	12.70 ± 5.21	0.41 ± 0.11
				2Bk/2Ck	40–100	9.57 ± 8.12	58.48 ± 5.58	18.26 ± 2.77	23.26 ± 4.98	1.38 ± 0.05	8.82 ± 0.08	27.59 ± 6.11	0.30 ± 0.06

SD *: Standard deviation; M: Management; SP: Soil sampling; Hor: Horizon; BD: Bulk density; OC: Organic carbon; *n* = Sample size. OC-CL: Old cultivated (tilled > 100 years) Calcisols; NC-CL: Newly cultivated (tilled < 12 years) Calcisols.

In general, the surface horizon (topsoil) was weakly developed with low SOC content ranging from 0.12% (OC-AR: B1-Ap) to 0.56% (NC-CL: PT: A5-Ap). In this sense, the management type (strongly mechanized) caused the soil homogenization by mixing the surface horizons in the first 40 cm. Due to the low SOC, they are not diagnostic horizons [38], so the C content was below the 0.2% (Tables 4 and 5). Similar results were obtained by [54,55] in CL in the Sfax region, near of the study area, stating that the natural SOC content in the Ap horizon of these soils was very low (<0.3%) due to climatic conditions, relief, and lithology. Calcium carbonate content in the deeper horizons (40–100 cm) was variable, with simultaneous presence of secondary precipitation (calcic horizons). According to [56], the soils developed from carbonate parent materials are common and belong to the main soil groups in North Tunisia.

In the remaining soils, the calcium carbonate content was not high, and due to texture (sandy) and the lack of diagnostic horizons, they were classified as AR. The presence of weakly developed AR derived from aeolian sediments has also been confirmed by [37].

Nevertheless, the carbonates' presence in these soils was expressed using the Calcaric qualifier (C1, C2, B1, B2).

3.2. Soil Bulk Density and pH in AR and CL

One of the problems that the soils in the study area have is bulk density (BD) quantification, since they are sandy soils with strong wind erosion, together with the high carbonate concentration. In this sense, the BD determination is very important, since it affects SOCS analysis [50–52].

The BD study did not show a clear trend; although in most cases BD decreased in depth, this behavior was expected, since in most cases, the BD reduction prevented an increase in the SOC concentration (Tables 4 and 5). In the superficial layer (0–40 cm), our results showed that BD on average were between 1.7 and 1.39 Mg m^{-3} for OC-AR and NC-CL, respectively; however, in sub-soil (40–100), the BD ranged between 1.69 and 1.35 Mg m^{-3} for NC-AR and NC-CL. It is important to note that BD was higher in AR compared to CL regardless of the study period (long-term and short-term) (Tables 4 and 5). The studied soils have shown that BD decreased significantly in NC-CL and OC-CL; in this line, [57] confirmed that in temperate zones, a decrease in BD is related to an increase in calcium carbonate content. BD values tended to be higher in surface horizons than in deep layers specifically in CL. This increase can be explained by the effect of tillage, which reduces the SOM content, increasing soil compaction and increasing the soil DB. This effect has been shown by [58] in soils with different land uses, indicating a BD increase in cropland. In addition, this BD increase was more important in the soil that was most intensively tilled.

Our results show differences in BD between CL and AR, and these differences may be due to soil type, management practices, and climatic conditions, in addition due to several factors, such as volume and rainfall intensity, drying and wetting of soil, land position, and crop type, among others [59]. According to [60], the time factor could be the most important factor that explains the BD variations in surface and subsurface. In fact, these authors reported that under conventional tillage, the general trend in surface at 15 cm depth was a BD increase during the cropping cycle except in the surface rows where BD was already high at the first measurement time.

The soil pH values showed that pH decreased slightly with increasing depth in newly and previously cultivated CL and AR (Tables 4 and 5). In the superficial layer, pH values were between 8.78 and 8.95 in NC-CL and between 8.94 and 9.17 in NC-AR. In the deep layer, pH values ranged from 8.74 to 8.93 in NC-CL and from 8.81 to 9.12 in NC-AR. In OC soil, pH values in superficial layers fluctuated between 8.78 and 9.29 in OC-CL and between 9.10 to 9.25 in OC-AR. In the deep layer, pH values varied between 8.74 and 9.19 in OC-CL and between 9.10 and 9.19 in OC-AR. These results were similar to those found by [61] in Sfax Tunisia in conventional tillage (cultivated soil) with alkaline pH (9.17 $\pm$ 0.76); since the SOC degradation and the $CaCO_3$ solubilization may affect pH, in this line, we suggest that the alkaline condition can be caused by the high concentration of the calcium carbonate.

3.3. Soil Organic Carbon Stock Concentration

All SOCS values of newly cultivated soils (<12 years) and old cultivated soils (>100 years) are shown in Tables 6 and 7. The results indicate important differences between SOCS in newly and previously cultivated soils regarding the soil type (CL or AR).

Table 6. Soil organic carbon stock in Arenosols.

Soil	M	SP	LU	Hor	Th (cm)	Gravel (%)	BD (Mg m^{-3})	OC (g kg^{-1})	SOCS Mg ha^{-1}	T-SOCS Mg ha^{-1}
AR	OC-AR n = (3 × 2)	B1	OG	Ap	40	1.15	1.701	1.25	8.407	40.783
				AC	60	0.60	1.645	3.30	32.376	
		B2	OG	Ap	40	1.91	1.692	2.90	19.252	35.260
				C	60	6.74	1.673	1.71	16.008	
		B3	OG	Ap	40	1.48	1,705	2.82	18.947	47.436
				AC	60	2.60	1.681	2.90	28.489	
		X		Ap	40	1.51 ± 0.28	1.70 ± 0.01	2.32 ± 0.93	15.535 ± 6.175	41.159 ± 7.363
				AC	60	3.31 ± 3.13	1.67 ± 0.02	2.64 ± 0.83	25.624 ± 8.552	
	NC-AR n = (3 × 2)	C1	AT	Ap	40	2.98	1.560	2.70	16.346	30.839
				C	60	4,32	1.530	1.65	14.493	
		C2	OG	Ap	40	0.66	1.632	2.90	18.806	28.303
				BC	60	0.88	1.681	0.95	9,497	
		C3	OG	Ap	40	0.09	1.670	1.45	9.677	16.239
				C	60	0.44	1.690	0.65	6.562	
		X		Ap	40	1.24 ± 1.53	1.62 ± 0.06	2.35 ± 0.79	14.943 ± 4.723	25.127 ± 4.367
				C	60	1.88 ± 2.13	1.63 ± 0.09	1.08 ± 0.51	10.184 ± 4.010	

M: Management; SP: Soil sampling; BD: Bulk density; OC: Organic carbon; SOCS: Soil organic carbon stock; T-SOCS: Total SOCS; n = Sample size. OC-CL: Old cultivated (tilled > 100 years) Calcisols; NC-CL: Newly cultivated (tilled < 12 years) Calcisols.

Table 7. Soil organic carbon stock in Calcisol.

Soil	M	SP	LU	Hor	Th (cm)	Gravel (%)	BD (Mg m^{-3})	OC (g kg^{-1})	SOCS Mg ha^{-1}	T-SOCS Mg ha^{-1}
CL	OC-CL n = (3 × 2)	M1	OG	Ap	40	6.91	1.621	1.31	7.907	25.661
				2Ck	60	7.47	1.591	2.01	17.754	
		M2	OG	Ap	40	0.81	1.610	2.60	16.608	39.796
				2Bk	60	2.38	1.342	2.95	23.188	
		M3	OG	Ap	40	23.54	1.330	5.40	21.965	33.607
				Ck	60	41.86	1.451	2.30	11.642	
		M4	OG	Ap	40	16.16	1.570	1.15	6.055	27.596
				2Ck	60	6.20	1.501	2.55	21.541	
		M5	OG	Ap	40	0.73	1.531	2.15	13.070	34.301
				2Ck	60	2.28	1.420	2.55	21.231	
		X		Ap	40	9.63 ± 10.00	1.53 ± 0.12	2.52 ± 1.72	13.121 ± 6.471	32.192 ± 5.536
				2Bk/Ck	60	12.04 ± 16.83	1.46 ± 0.09	2.47 ± 0.35	19.071 ± 4.600	
	NC-CL n = (3 × 2)	A1	OG	Ap	40	1.56	1.570	2.71	16.753	38.977
				2Ck	60	3.80	1.351	2.85	22.224	
		A2	OG	Ap	40	4.28	1.541	3.51	20.710	42.117
				Ck	60	0.64	1.355	2.65	21.407	
		A3	OG	Ap	40	10.85	1.412	3.95	19.889	45.815
				2Ck	60	21.60	1.371	4.02	25.926	
		A4	AT	Ap	40	14.47	1.032	4.90	17.300	38.721
				Ck	60	9.83	1.461	2.71	21.421	
		A5	PT	Ap	40	3.24	1.370	5.60	29.694	49.371
				2Bk	60	11.99	1.355	2.75	19.677	
		X		Ap	40	6.88 ± 5.51	1.39 ± 0.22	4.13 ± 1.14	20.869 ± 5.209	43.000 ± 3.7625
				2Bk/2Ck	60	9.57 ± 8.12	1.38 ± 0.05	3.00 ± 0.58	22.131 ± 2.316	

M: Management; SP: Soil sampling; BD: Bulk density; OC: Organic carbon; SOCS: Soil organic carbon stock; T-SOCS: Total SOCS; n = Sample size. OC-CL: Old cultivated (tilled > 100 years) Calcisols; NC-CL: Newly cultivated (tilled < 12 years) Calcisols.

The SOCS analysis showed that on average, the SOCS content in CL was 20.9 Mg ha^{-1} and 13.1 Mg ha^{-1} in topsoil (0–40 cm depth) for NC-CL and OC-CL, respectively. In sub-soil (1 m depth), the SOCS was 43.0 Mg ha^{-1} (NC-CL) and 32.2 Mg ha^{-1} (OC-CL). In this line, [62] in dryland of southeastern Spain found 52 Mg ha^{-1} and 70 Mg ha^{-1} for 0.5 m and 1 m depth, respectively, and [63] in southern Spain reported 50.1 Mg ha^{-1} at 0.25 m depth and 82 Mg ha^{-1} at 0.75 m depth. These differences in SOCS between our results and the results reported by [62,63] could be explained by the impact of tillage that increases the SOC depletion and reduces the biomass generation. In addition, these discrepancies (low SOCS content in the studied soils) may reflect a combination of different factors such as intensive farming practices, climate conditions, soil types, soil age, and topography area [64,65].

In the AR case, on average, the SOCS contents were as follows: 14.9 Mg ha^{-1} and 25.1 Mg ha^{-1} for 0.4 m and 1 m depth, respectively, in NC-AR, and 15.5 Mg ha^{-1} and 41.2 Mg ha^{-1} at 0.4 m and 1 m depth, respectively, in OC-AR. Other authors such as [66], for soil groups in Peninsular Spain (FAO soil map of Peninsular Spain), reported low SOCS content in AR (22.2 Mg ha^{-1}) in soil profiles deeper than 1 m. Furthermore, [8] indicated that the SOC content (average values) in the upper 1 m was 31 Mg ha^{-1} for sandy AR. These differences between our data and the data indicated by other authors may be due to soil texture (sandy soils) and tillage. In NC-AR, the SOCS at surface depth (Ap horizon) was higher than in the C horizon. In this line [67], argued that the SOCS on surface horizon was greater than in deep soil due to tillage and in turn increasing the physical protection of native SOC from microbial decomposition. We can increase C inputs into surface soil by enhancing crop biomass and in turn residue return. With respect to OC-AR, this relation was inverse (SOCS increased in AC horizon); this effect can be explained by soil texture (sandy soils) and tillage, because native SOC can be reduced on the surface, which may be attributed to soluble organic compounds that can leach into deeper layers, increasing the soil aggregates [68,69].

3.4. Effects of Management Time on Soil Organic Carbon Stock

The results indicated important differences between SOCS (0–100 cm) in newly and previously cultivated soils regarding the soil type (CL or AR). In NC-CL, the SOCS (0–100 cm) content ranged from 38.7 Mg ha^{-1} (NL-CL-AT) to 49.4 Mg ha^{-1}, (NC-CL-PT); however, lower SOCS were obtained for OC-CL, varying between 25.7 Mg ha^{-1} (OC-CL-OG) and 39.8 Mg ha^{-1} (OC-CL-OG). In the CL case, it is important to note that the land use affected the SOCS content, since on average (0–100 cm), the centenary OG (OC-CL) had a 25.6% lower SOCS than the young OG (NC-CL). However, in depth (40–100 cm), no differences were found according to the land use age (OC and NC) with respect to SOCS. Another aspect to highlight is that in the different crops developed (olive, almond, and pistachio) in NC-CL, the pistachio (PT) had the highest SOCS content (49.4 Mg ha^{-1}), whereas the lowest SOCS values were found in almond tree (AT) (38.7 Mg ha^{-1}).

However, the study of AR has shown that the SOCS content on average in the Ap horizon (0–40 cm) in NC and OC were very similar (OC-AR: 15.5 Mg ha^{-1}; NC-AR: 14.9 Mg ha^{-1}), but nevertheless, in depth (40–100 cm: AC/BC/C horizon), significant differences were found (OC-AR: 25.6 Mg ha^{-1}; NR-AR: 10.2 Mg ha^{-1}). When comparing both soils (AR and CL), significant differences were observed between NC-CL and NC-AR; however, no significant differences were observed between OC-CL and OC-AR. The highest SOCS contents were obtained in NC-CL regardless of the land tillage time.

In OC-CL, the SOCS (32.2 Mg ha^{-1}) was significantly lower compared to NC-CL (43 Mg ha^{-1}). However, the SOCS in OC-AR (41.2 Mg ha^{-1}) increased with respect to NC-AR (25.1 Mg ha^{-1}) (Tables 6 and 7). These results indicate that the SOCS in CL and AR are linked to land management duration (OC > 100 years and NC < 12 years). In this line, our results are accordance with [70] in CL in Turkey, which justified an SOC reduction with intensive soil management under strong wind and water erosion conditions, clarifying that under these conditions, the SOM is rapidly mineralized in the soil. In addition, soil management over time may deteriorate the aggregates' stability [69] and reduce the CL quality, affecting the soil water storage capacity in rainfed OG [70], these processes therefore could explain the SOM reduction and the SOCS decreasing in the surface horizon.

Several studies have found an increase in the SOC content in AR cultivated more than 20 years in different arid areas [71–73]. This is in concordance with our study; however, according to [74], the SOC could be depleted under intensive tillage, which is in discrepancy with our findings. In this sense, [75], in the same study area as [76], showed the olive roots' presence within the sands; however, it was observed that olive roots were absent in the calcareous crusts. In the study soils, more than 90% of AR had sandy texture; for this reason, we suggest that the SOC increase could be due to the olive roots' presence since the calcareous crusts are not present. Moreover, the tillage can affect a large part in the accumulation of the olive roots (along the profile), which may explain our findings. In the literature, the tillage is assumed to alter the SOCS and also to reduce the SOC quantity and to deteriorate the aggregates in the soil [10,69]. However, long cultivation periods with heavy tillage showed a positive effect on SOCS in AR, but due to the climatic conditions (semi-desert), more research should be carried out in AR to be able to identify the mechanism that explains this SOCS increase in AR.

Another question to highlight is that OC could be influenced by the abundance of the olive root mass. In this sense, it should be noted that the olive tree renews its roots every year and that the root system is better developed in the ventilated area (AR) than in compacted soils (CL). Another issue to point out is the addition of the organic amendments, so that some sources of organic amendments may accelerate the SOC mineralization. In the study area, in some plots, different organic amendments were added (B1, A1, A2, and M1), the main consequence was a SOCS reduction in the soil surface with respect to the plots without amendments (C1, A4, A5, and M3) (Tables 2 and 3). However, in other cases, there was a SOCS increase in the soil surface in modified plots (A3, B2, C2, and M2) compared to the unmodified plots (M4). This SOCS variability could be explained by the results obtained by [76], who suggested that depending on the organic amendment type, the SOC balance (gain or loss of SOC) is conditioned by the incubation period and the organic amendment type. The increase in SOC of green manure derived from olive pruning residues (dried and crushed shoots and leaves of olive trees) is too limited (0.13 mg g^{-1}), and the SOC balance (between the day after amendment and 120 days after) (−0.45) compared to the SOC gain of compost of manure and olive husk and palm-leaf-based compost are (0.28 mg g^{-1}) and (0.31 mg g^{-1}), respectively. The SOC balance is (−0.02) and (−0.05) in both compost types. These results could explain the SOC variability in the study area. However, we must be careful, as the organic amendments addition can be confounding as they lead to variability of the SOC content.

In Egypt (semi-desert conditions), Ref. [77] proposed a direct relation between the cropping history and SOCS (longer cultivation period implies the higher SOCS). This result is in agreement with AR and in disagreement with CL. We suggest that the soil type plays an important role in the depletion or the gain of SOC. In the study area, AR are efficient for SOCS accumulation, especially after 100 years of cultivation and tillage, and they could be carbon sink and may be involved in reducing carbon dioxide (CO_2) emissions. In fact, it has been reported that soil might represent a sink for atmospheric CO_2 [78–80].

3.5. Uncertainties and Bias

The complexity of these soils study is due to the continuous movement of the surface particles by the wind (eolian processes). For this reason, in demi-desert areas, few studies have been developed to define SOCS thresholds. In this line, all soil samples were taken at the same time (synchronic approach) under different management practices at known durations from an initial reference state, and the SOCS was compared under this initial reference state [53]. However, due to eolian processes (displacement of particles by the wind), it could be useful to carry out different samplings throughout the year, to reduce the wind effect, this question is relevant to establish the thickness of the surface horizon.

However, despite the mistakes, the SOCS study in these soils type (AR and CL) under these climatic conditions could help us to promote strategies to combat the desertification and climate change. So, this research constitutes a preliminary assessment of SOCS estimation with different land uses and different management practice durations.

4. Conclusions

The main conclusions derived from this research depend on land use (olive grove, almond tree, and pistachio tree), land management (tillage and amendments) the practice's duration (old plantations > 100 years and new plantations < 12 years) and soil type (Arenosols and Calcisols) in semi-desert conditions. In this line, the crop type, tillage, and tillage duration affect to soil bulk density, pH, and SOC for the same soil type.

On average, the SOCS for woody crops in semi-desert areas in CL is 43.0 Mg ha^{-1} and 32.2 Mg ha^{-1} (0–100 cm depth) for NC and OC, respectively, and with 40 cm depth, the SOCS is 20.9 Mg ha^{-1} (NC) and 13.2 Mg ha^{-1} (OC). In the case of the AR, the SOCS is 25.1 Mg ha^{-1} and 41.2 Mg ha^{-1} (0–100 cm depth) for NC and OC, respectively, and with 40 cm depth, the SOCS is 14.9 Mg ha^{-1} (NC) and 15.5 Mg ha^{-1} (OC). According to this, in dryland (semi-desert conditions), some soils could have a good capacity to increase soil organic carbon with certain management practices and duration specifically, the AR could increase the SOCS after 100 years of cultivation and tillage; however, the CL the SOC can be reduced.

Thus, SOCS content variations were detected and have established pistachio as the most efficient woody crop related to carbon storage (49.4 Mg ha^{-1}) under the soils and climatic conditions analyzed in the short term. Therefore, good information to better understand the dynamics of soil organic carbon storage could help to develop and consolidate the Framework of the United Nation Convention to Combat Desertification (UNCCD) on the one hand and to minimize greenhouse gases on the other.

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