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Impact of Arboriculture on Carbon Sequestration (case of Olive and Citrus Cultivations)

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Abstract

Soil organic carbon (SOC) sequestration plays a crucial role in mitigating climate change by reducing greenhouse gas emissions, as soil acts as a natural carbon reservoir. The main objective of this study was to investigate the effect of arboriculture, particularly citrus and olive growing, on soil organic carbon stocks under semi-arid conditions of the agricultural workshop of Mazagran at Mostaganem. To do this, we measured the quantity of carbon using the soil of the same study area according to several soil depth levels such as: (0-15 cm, 15-30 cm, 30-50 cm, 50-100 cm). The SOC stock varies significantly ($p < 0.05$) between the different land use modes, the highest value under olive cultivation ($32.63 \text{ Mg C ha}^{-1}$) is recorded at the level of the stratum going from 50 to 100 cm and the highest value under citrus cultivation ($24.29 \text{ Mg C ha}^{-1}$) is recorded at the surface stratum ranging from 0 to 15 cm. The lowest stock is recorded at ground level under citrus cultivation in the 3rd stratum ranging from 30 to 50 cm, with $6.33 \text{ Mg C ha}^{-1}$. The variation in OC distribution based on land use and depth can be attributed to differences in plant inputs (both in quantity and quality) between species, as well as variations in root distribution and depth, which influence the storage and stabilization of OC. Consequently, land use affects SOC stocks both at the surface and at depth.

Keywords: Carbon sequestration, Soil layers, Citrus cultivation, Olive cultivation, Land use, Mostaganem.

Introduction

Carbon is found in the atmosphere primarily in the form of carbon dioxide (CO₂), while it can also be present in the soil in organic and inorganic forms. During the period from 1850 to 2012, the concentration of CO₂ in the atmosphere is estimated to have increased by 111 parts per million (ppm), according to data from the World Meteorological Organization (Andres et al., 2012). The main sources of increasing CO₂ concentration in the atmosphere come from human activities, including the consumption of fossil fuels, deforestation for agricultural land expansion, and the burning of forest biomass. These anthropogenic activities contribute to approximately 32 billion metric tons of CO₂ emissions each year, with deforestation accounting for 20% of these emissions globally. These emissions are estimated to constitute around a third of total greenhouse gas (GHG) emissions. Additionally, between 0.7 and 2.1 G t C yr⁻¹ of carbon per year was lost due to land use change and associated processes (Derrien et al., 2016). Soils represent the largest carbon reservoirs in agroecosystems and have significant potential for storing carbon over long periods. Many research methods have been developed to quantify soil organic carbon (SOC) on a global scale. The most recent estimates indicate that soils contain between 1500 and 2500 gigatons (Gt) of carbon, or 2 to 2.5 times more than the atmosphere (560 Gt) and four times more than the biotic pool, up to at a depth of 1 meter (Smith and Powlson, 2018). Globally, soils in agricultural ecosystems play a critical role in sequestering approximately 2.1 billion tonnes of carbon per year (Minasny et al., 2017). The Mediterranean region is strongly affected by climate change, experiencing changes in temperatures, an intensification of summer and periods of drought as well as low and irregular precipitation rates (Derrien et al., 2016).

Nowadays, soils are attracting more and more interest, because they are at the heart of major global challenges such as food security, water supply, climate change or the preservation of biodiversity (Merabtene, 2021). According to Benouadah et al. (2020), the evolution of soils and their physical, chemical and biological characteristics, in particular with regard to their agricultural production function, is closely linked to their organic status, that is to say to the quantity and quality of their organic matter. Indeed, it is now clear that soil organic matter (SOM) plays a crucial role both agronomically and environmentally, particularly in highly altered soils of tropical agroecosystems (Derrien et al., 2016). It offers the possibility of storing and providing nutrients to plants, stabilizing aggregates, regulating pollutants, reducing GHGs and serving as a source of energy for organisms (FAO, 2017).

The origin of these organic materials lies in the natural capture of carbon dioxide by higher plants, as well as by soil algae, lichens and photosynthetic bacteria thanks to photosynthesis. Additionally, photosynthesis allows plants to use solar energy to absorb CO₂ from the air and produce plant matter. When plants die, their tissues are successively transformed in the soil by physical, chemical and biological phenomena. These transformations lead to more or less stable or labile compounds, which contain on average around 58% organic carbon (Arrouays, 2008). According to Benouadah et al., (2023), the way in which agricultural land is managed and used has a significant impact on the dynamics of organic matter and its stability. It is essential to understand the potential of agricultural soils based on uses and practices (Arrouays, 2008). **As agroforestry can contribute to people's well-being and livelihood. It reduces greenhouse gas emissions, improves soil fertility status, provides ecosystem services, generates assets and income from carbon (Sow et al., 2024).**

Historical research on carbon dynamics in soil has mainly focused on the 0-30 cm layer, considered the most important by agronomists. It is important to note that approximately half of soil carbon is found below 30 cm depth, for most soils around the world, including mainland France. This proportion, however, varies depending on land use (Smith and Powlson, 2018).

This study aims to better understand the behavior of agricultural soils under fruit arboriculture, in particular citrus and olive orchards, in semi-arid Mediterranean conditions, in relation to organic carbon storage. This objective is all the more important as citrus and olive cultivations occupy considerable areas in Algeria. Indeed, citrus fruits are grown on approximately 45,000 hectares, while the olive tree is present on 440,000 hectares according to the agricultural services department of Mostaganem (ASDM, 2024).

The main objective of this study was to assess fluctuations of the soil organic carbon stocks according to their occupations in the Mazagran farm in Mostaganem. To do this, we quantified organic carbon (i) according to the main land uses represented by olive and citrus cultivations in the same study area, and (ii) according to four soil layers; from 0 to 15 cm, from 15 to 30 cm, from 30 to 50 cm and from 50 to 100 cm.

Materials and methods

Study area. The study was carried out at the Agricultural Workshop, located in the Mazagran municipality, 4 km south of the Mostaganem city in the northwest of Algeria between the Lambert coordinate points 35°53' 37'' N, 0°4' 52'' and 35° 53' 04'' N with an altitude of 125 to 151 m, it is delimited by the commune of Mazagran to the West, Hassi Mamèche to the

South and Douar Djedid to the East. The area of the farm is 62.74 ha, of which the area cultivated with citrus fruits since 1950 represents 2.80 ha, or 4.6% of the total area occupied by citrus fruits with 135 orange trees, 360 lemon trees and 10 grapefruit trees and the area of olive cultivation represents 6 ha, or 10% of the total area with approximately 1000 trees (ASDM, 2024). Its climate is semi-arid Mediterranean with temperate winters. Rainfall varies between 350 and 500 mm/year and the average annual temperature is 18.3°C (ASDM, 2024).

Soil analysis. Soil samples were collected from the experimental site in the same day (Mars 5th, 2024), with three replicates according to: (i) the main land uses: soil under olive cultivation (SOc) and soil under citrus cultivation (SCc) in Mars 2024, and (ii) the four soil layers; from 0 to 15 cm, from 15 to 30 cm, from 30 to 50 cm and from 50 to 100 cm.

Finally, a total of 24 [$3(\text{SOc}_{0-15 \text{ cm}}) + 3(\text{SOc}_{15-30 \text{ cm}}) + 3(\text{SOc}_{30-50 \text{ cm}}) + 3(\text{SOc}_{50-100 \text{ cm}}) + 3(\text{SCc}_{0-15 \text{ cm}}) + 3(\text{SCc}_{15-30 \text{ cm}}) + 3(\text{SCc}_{30-50 \text{ cm}}) + 3(\text{SCc}_{50-100 \text{ cm}})$] soil samples were collected for the SOCS estimation.

It was important to analyze additional factors influencing SCOS variation, including:

- Bulk density (BD) in g cm^{-3} by the direct sampling method, using a steel cylinder with a volume of 252.2 cm^3 (Blake and Hartge, 1986).
- Coarse element load (CP) in g g^{-1} : the replicates of each soil sample were oven-dried for 24 h at 105 °C and sieved at 2 mm to remove coarse element load, pH by electrometric method 2:5 (m/v), using pH meter (Starter 200, Ohaus), salinity in $\mu\text{S cm}^{-1}$ by electrical conductivity (EC) method 1:5 (m/v), using a conductivity meter (Consort), total carbonate (Total CaCO_3 content) in % by Bernard calcimeter method using HCl acid (Mathieu et al., 2015).
- Active carbonate (Active CaCO_3 content) in % by Drouineau-Galet method, using ammonium oxalate (Drouineau, 1942).
- Mineral fractions in % by Robinson pipette method, considered fractions being sand (50- 2000 μm), silt (2-50 μm), and clay (0-2 μm) (Gee and Or, 2002).
- Soil organic carbon (SOC) in % by the modified Walkley and Black method, based on the oxidation of OC by potassium dichromate $\text{K}_2\text{Cr}_2\text{O}_7$ in sulfuric acid (Gillman et al., 1986).
- Nitrogen total (N) by the Kjeldhal method (Bremner et al., 1982).

The soil samples were air dried, crushed and passed through a 2 mm diameter sieve.

According to Benouadah et al. (2023), the SOC stock was calculated as:

$$\text{SOC stocks (Mg C ha}^{-1}\text{)} = 0.1 * \text{C} * \text{BD} * \text{t} * (1 - \text{CP})$$

Where:

- SOC stock is a soil organic carbon stock (Mg C ha^{-1});
- C is the carbon content (g C kg^{-1} soil);
- BD is the bulk density (g cm^{-3});
- t is the thickness of the soil horizon (cm);
- CP is the coarse element load (g g^{-1} of soil).

Then, we determined the OCS over the depths of 0-30 cm, 0-50 cm and 0-100 cm by summing the SOC of all soil layers up to the target depth by the following formula (Bounouara et al., 2017):

Sum (SOCS) total = (SOCS) 1st layer + (SOCS) 2nd layer + + (SOCS) n layer

Data Analysis. One-way analysis of variance tests (ANOVA) were used to compare means and determine the significant differences. Correlation analysis was used to demonstrate the relationship between the SOCS and soil physicochemical properties, soil occupations (arboriculture: case of olive and citrus cultivations) and different soil layers. This analysis is conducted by R Software (Core Team, 2020).

Results and discussion

Variation of the Studied Parameters according to the soil occupations and soil layers.

Mineral fractions. From the results illustrated in Table 1, it is observed that for the majority of the soil layers studied have very high proportions of sand (60% - 93%), but the difference is observed in silts and clays fractions, since the 4th layer of the SOc has the highest rate of silts (38%) compared to the other soil layers (5% for the 1st layer, 11% for the 2nd layer and 3% for the 3rd layer) of the SOc and (11% for the 1st layer, 7% for the 2nd layer, 12% for the 3rd layer and 18% for the 4th layer) of the SCc, while the clay rates are very low, between 1% and 5% for all the soil layers of the two species. Based on the texture triangle classification, the studied soil layers exhibit different textural classes:

Sandy: for (1st and 3rd) layers of the SOc and the 2nd layer of the SCc.

Sandy-loamy: for the 2nd layer of the SOc and (1st, 3rd and 4th) layers of the SCc.

Loamy-sandy: for the 4th layer of the SOc and which represents the most balanced texture (USDA, 2008).

According to the textural class, the 4th layer of the SOc is the layer accumulation, the reason why the texture improves and becomes balanced, while the other soil layers are part of the sandy and sandy-loamy class and therefore have high permeability and induce leaching of fine elements (USDA, 2008).

Table 1. Granulometric composition of the studied soils.

Soil layers	Granulometry	
	SCc	SOc
(0-15cm)	<p>4% 5% 6% 85%</p> <ul style="list-style-type: none"> ■ C ■ CS ■ FS ■ S 	<p>5% 4% 1% 90%</p> <ul style="list-style-type: none"> ■ C ■ CS ■ FS ■ S
	Textural class : sandy-loamy	Textural class: sandy
(15cm-30cm)	<p>2% 4% 3% 91%</p> <ul style="list-style-type: none"> ■ C ■ CS ■ FS ■ S 	<p>5% 4% 7% 84%</p> <ul style="list-style-type: none"> ■ C ■ CS ■ FS ■ S
	Textural class: sandy	Textural class : sandy-loamy
(30cm-50cm)	<p>4% 1% 11% 84%</p> <ul style="list-style-type: none"> ■ C ■ CS ■ FS ■ S 	<p>4% 1% 2% 93%</p> <ul style="list-style-type: none"> ■ C ■ CS ■ FS ■ S
	Textural class : sandy-loamy	Textural class: sandy
(50cm-100cm)	<p>1% 9% 9% 81%</p> <ul style="list-style-type: none"> ■ C ■ CS ■ FS ■ S 	<p>2% 5% 33% 60%</p> <ul style="list-style-type: none"> ■ C ■ CS ■ FS ■ S
	Textural class : sandy-loamy	Textural class : loamy-sandy

C: clay; FS: fine silt; CS: coarse silt; S: sand.

Bulk density. The bulk density of the soil generally reflects the state of compaction of the soil and indirectly, the total porosity; it is one of the most important parameters in studies on soil structure (Mathieu et al., 2015). According to the Figure 1a, it can be seen that all the studied have an ideal bulk density for plant growth since they are less than 1.60 g cm^{-3} (USDA, 2008), from $1.059 \pm 0.082 \text{ g cm}^{-3}$ to $1.269 \pm 0.060 \text{ g cm}^{-3}$ for SOc, and from $1.055 \pm 0.011 \text{ g cm}^{-3}$ to $1.297 \pm 0.018 \text{ g cm}^{-3}$ for SCc. In addition, they have an ideal structure that is favorable to root development since they are less than 1.80 g cm^{-3} (USDA, 2008). According to Mathieu et al. (2015), a high apparent density value means that the voids are reduced and the particles are highly compacted, this means that the soils studied are light (good porosity).

pH. The results obtained (Figure 1d) indicated that the 4th layer of the SOc has a weakly acidic pH (6.48 ± 0.125) and the 1st layer of the SCc has a neutral pH (7.42 ± 0.081), while the pH of the soils of the other layers are basic, with slight variations (between 7.58 ± 0.025 and 7.73 ± 0.012). The pH, close to 8, is imposed by the presence of calcium and magnesium carbonates and cannot be modified by agricultural practices. In the absence of carbonates, the soil pH is neutral or acidic, but apparently the basicity of these soils may be due to the quality of irrigation water which may be rich in sodium. pH is one of the strong predictors of bacterial community composition and diversity (Mathieu et al., 2015).

Salinity. According to the Figure 1c, the soil electrical conductivity of the two species (olives and citrus) is between $120.66 \pm 0.950 \mu\text{S cm}^{-1}$ and $269.33 \pm 0.333 \mu\text{S cm}^{-1}$.

According to USDA (2008), a soil with an $\text{EC} \leq 500 \mu\text{S cm}^{-1}$ is a non-salty soil, and the effect of the latter on the yield is negligible, which is entirely consistent with the results we obtained.

Total and active limestone. As shown in Figures (1d and 1f) and according to USDA (2008), the studied soils contain low levels of total CaCO_3 : $8.15 \pm 1.02\%$, $5.31 \pm 0.98\%$, $6.07 \pm 0.77\%$ and $5.36 \pm 0.53\%$, respectively for the 1st layer, 2nd layer, 3rd layer and 4th layer of the SOc, and $7.42 \pm 1\%$, $8.86 \pm 0.88\%$, $6.71 \pm 0.66\%$ and $5.36 \pm 0.97\%$, respectively for the 1st layer, 2nd layer, 3rd layer and 4th layer of the SCc and active CaCO_3 (1.5% for the SOc and 2% for the SCc), so they are weakly calcareous soils in their entirety.

Organic carbon. Soil organic carbon (SOC), especially soil organic matter (SOM), is a cost-effective and informative indicator of soil quality and agricultural sustainability as it promotes the soil physical, biological and chemical properties (USDA, 2008).

The analytical results (Figure 1f) showed that the SOc of the 2nd layer and the SCc of the 1st layer have the highest OC rate with $1.535 \pm 0.374 \text{ g kg}^{-1}$ and $1.535 \pm 0.535 \text{ g kg}^{-1}$ respectively

and while for the other layers, the SOc has an OC rate between $1.105 \pm 0.125 \text{ g kg}^{-1}$ and $0.616 \pm 0.082 \text{ g kg}^{-1}$ and the SCc has an OC rate between $0.616 \pm 0.078 \text{ g kg}^{-1}$ and $0.244 \pm 0.048 \text{ g kg}^{-1}$. SOC and therefore OM is not uniformly distributed in the soil. Its concentration decreases sharply with depth. The highest concentrations are found in the surface organic horizons where the microbial population is intense (Derrien et al., 2016).

According to USDA (2008), we can deduce that:

The SOc of the 2nd layer and the SCc of the 1st layer are average soils in OM.

The SOc of the other layers (1st, 3rd and 4th) and the SCc of the 2nd layers are soils poor in OM.

The SCc of the other layers (3rd and 4th) is a soil very poor in OM.

Soils with organic matter content greater than 5% are rare in arboriculture, if the organic matter content is insufficient, it is necessary to consider influencing it through cultural practices in order to maintain healthy activity in the soil (Kuster et al., 2017).

According to Minasny et al. (2017), the type of vegetation influences the organic matter content of agricultural soils. It should also be noted that various research studies have shown that the lower the clay content of the soil, the lower the organic matter content (Akpa et al., 2016), which is entirely consistent with the results of our study.

Total nitrogen. According to Kuster et al. (2017), N is the most important nutrient in arboriculture as a constituent of organic compounds (amino acids, nucleic acids and proteins) and chlorophyll. A deficiency or excess of N disrupts the physiological balance of trees and leads to an unfavorable relationship between vegetative growth and vegetative development, or qualitative defects in fruits.

The results obtained (Figure 1g) indicated that the SOc of the 2nd layer and the SCc of the 1st layer have the same nitrogen content (0.127%). While for the other layers, the SOc has nitrogen content between $0.053 \pm 0.008\%$ and $0.095 \pm 0.011\%$ and the SCc has a nitrogen content between $0.021 \pm 0.003\%$ and $0.053 \pm 0.007\%$. According to Mathieu et al. (2015), it can be seen that our two soils are very poor in nitrogen. The ideal timing of N application depends on the clay content of a soil (N mobility in the soil): N application is made from the beginning of March in clayey soils and shortly before flowering (end of March/beginning of April) in clay-poor soils (Kuster et al., 2017).

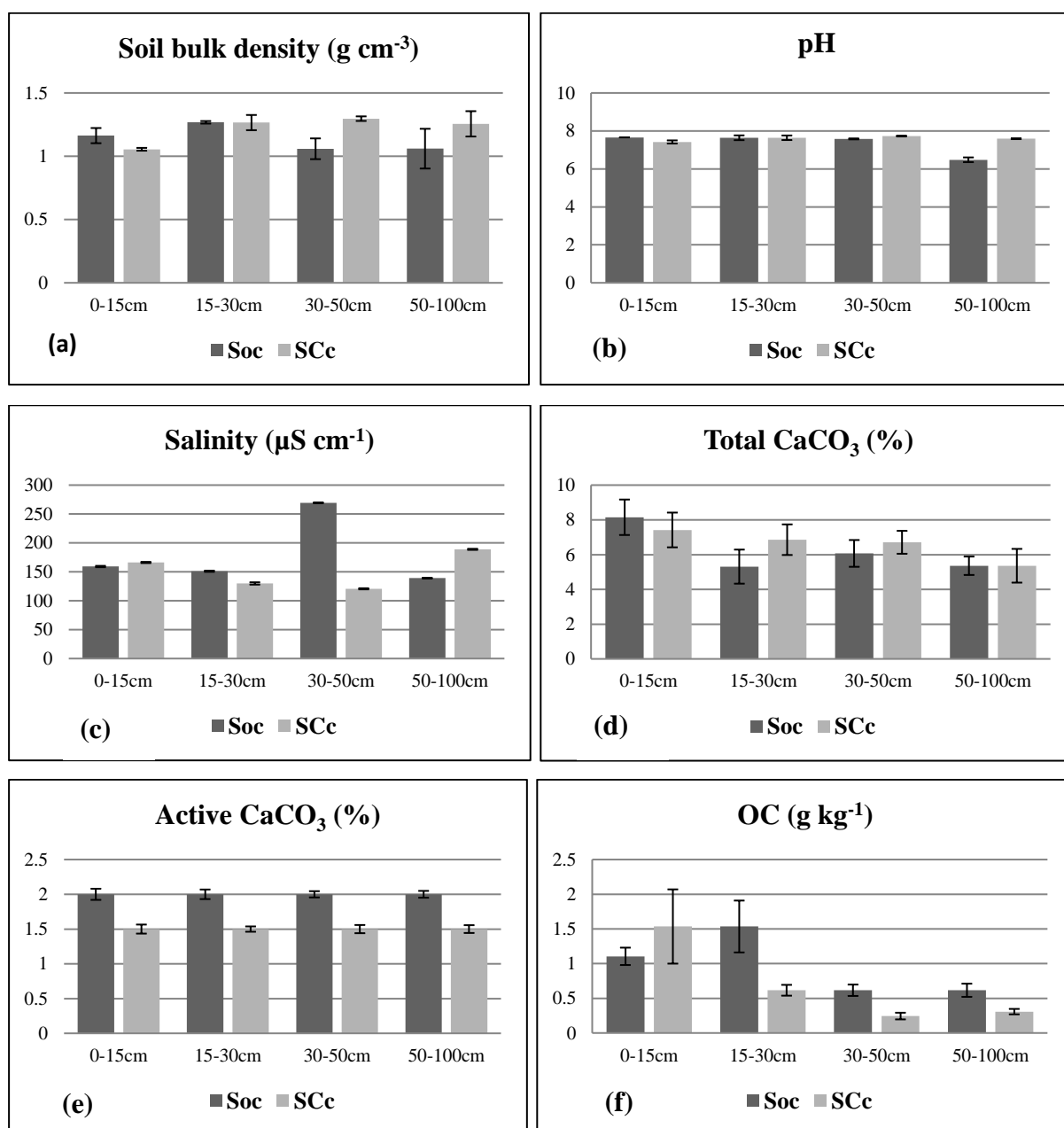
C:N ration. The soils of both species have good mineralization of OM.

We note in Figure 1h that the SOc of the 2nd layer and the SCc of the 1st layer have the same value of the C:N ratio (12.09) which is slightly high. While for the other layers, the SOc has a

C/N value between $11.62 \pm 0.980\%$ and $11.63 \pm 1.04\%$ and the SCA has a C:N value between $11.62 \pm 0.99\%$ and $11.84 \pm 0.094\%$.

The C:N ratio is often used to predict the stability of simple organic matter in the soil. A material with low C:N (4 to 12) will be quickly mineralized by providing a lot of mineral nitrogen. Therefore the soil has a significant biological activity leading to a rapid decomposition of organic matter (Akpa et al., 2016)

The degradation of a material with a high C:N (15 to 20) will conversely cause the immobilization of soil nitrogen by microorganisms (FAO, 2017).



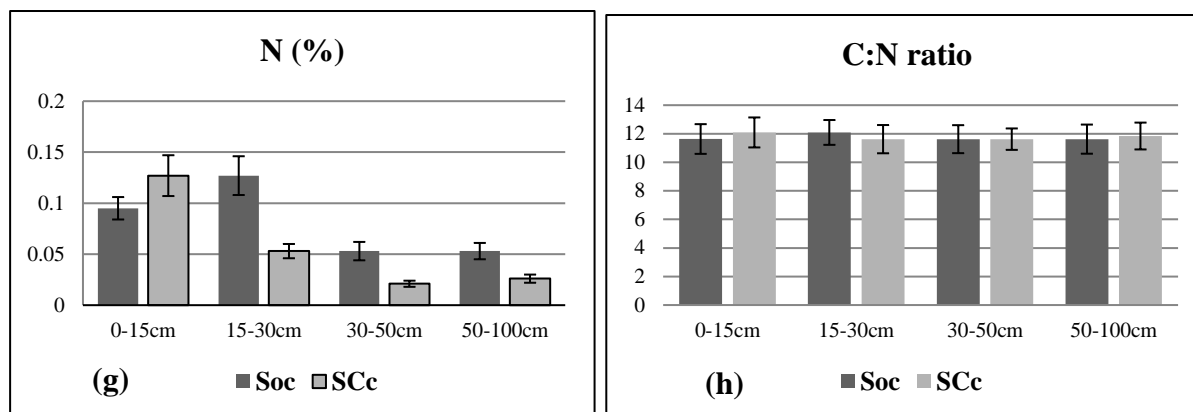


Figure 1. Variation of (a) bulk density (g cm^{-1}), (b) pH, (c) Salinity ($\mu\text{S cm}^{-1}$), (d) Total limestone (%), (e) Active limestone (%), (f) Soil organic carbon (g kg^{-1}), (g) total nitrogen (%) and (h) C:N ratio according to the soil occupations and the soil layers.

Variation of SOC stock. According to Benouadah et al. (2023), SCOS is influenced by agricultural land use, cultivation practices, depth and soil physicochemical parameters.

1. Variation of CO stock according to land use. Figure 2 highlights the effect of the land use on SOCS, the average stock is $15.41 \text{ Mg C ha}^{-1}$ for SCc and $23.54 \text{ Mg C ha}^{-1}$ for SOc.

There is a lack of synergy in the distribution of SCOS values; The SOC stock varies significantly ($p < 0.05$) between land use modes, with olive cultivation storing substantially more carbon in deeper layers than citrus cultivation, with the highest value recorded under olive cultivation ($32.63 \pm 4.829 \text{ Mg C ha}^{-1}$) at the level of the layer ranging from 50 to 100 cm. The lowest stock is recorded at soil level under citrus cultivation in the 3rd layer from 30 to 50 cm, with $6.33 \pm 0.088 \text{ Mg C ha}^{-1}$.

a. Variation of SCOS under citrus cultivation. The highest stock is $24.29 \pm 0.259 \text{ Mg C ha}^{-1}$ recorded for the superficial layer of 15-30 cm, while the lowest value ($6.33 \pm 0.088 \text{ Mg C ha}^{-1}$) is noted for the layer of 30-50 cm. The 1st layer is the best represented with 39.40% of the organic carbon stored. A negative correlation ($p < 0.01$) was found between the bulk density and the SCOS (Figures 1a and 2), could be explained by the content of the organic matter more or less high of this layer compared to the other layers and which is characterized by a good structure, which favors a good development of the root system.

b. Variation of SCOS under olive cultivation. The highest stock ($p < 0.05$) is $32.63 \pm 4.829 \text{ Mg C ha}^{-1}$ recorded in the 4th soil layer of 50-100 cm. The lowest value is $13.05 \pm 0.240 \text{ Mg C ha}^{-1}$ recorded in the 3rd layer of 30 to 50 cm. The 50-100 cm layer is the best represented for both types of crops, representing 34.65% of the stored organic carbon. The result of the correlation analysis reveals that the SOC stock has: a positive correlation ($p < 0.01$) with (i) silt and a negative correlation ($p < 0.01$) with (ii) pH. The positive correlation ($p < 0.01$)

between silt (Table 1) and SOCS (Figure 2) could be explained by the characteristics of silt, which acts as a water retention and nutrient accumulation factor by blocking fine particles. The ideal is a slightly acidic soil (6.5) which is suitable for most plantations. Microorganisms like this type of soil (Kuster et al., 2017). The biological activity of the soil and the assimilation of most nutrients depend on the pH (Kuster et al., 2017). This is why any abrupt change in pH should be avoided, in particular by excessive liming. The ideal pH in arboriculture is between 6.0 and 7.5. It is possible to increase it by liming. However, it is difficult to decrease it, for example by using acidifying fertilizers, due to the strong buffering capacity of calcium carbonate (Kuster et al., 2017). There is no similarity in the distribution of SCOS between the soil layers of the two species. This variation in the vertical distribution of SOCS according to land use can be explained by the difference in root depth according to the species occupying the soil, plant roots contributing primarily to the formation of soil organic matter (Benouadah et al., 2020), according to Benouadah et al. (2023), the variation in SCOS would be linked to the activity and length of the roots rather than to the root mass. In addition, living roots provide their environment with energy substances in significant quantities, it appeared in a work carried out, that these energy substances are easily assimilated, stimulating the rhizospheric microflora (Benouadah et al., 2020). This variation could also come from the difference in plant inputs that differ in quantity and quality between species (Poirier et al., 2018), as well as the composition of above-ground and below-ground plant tissues between species (Benouadah et al., 2023). The results of Benslimane et al. (2023) reinforce this hypothesis since they found that shrubs had the deepest roots, followed by trees and that herbaceous plants had the shallowest roots.

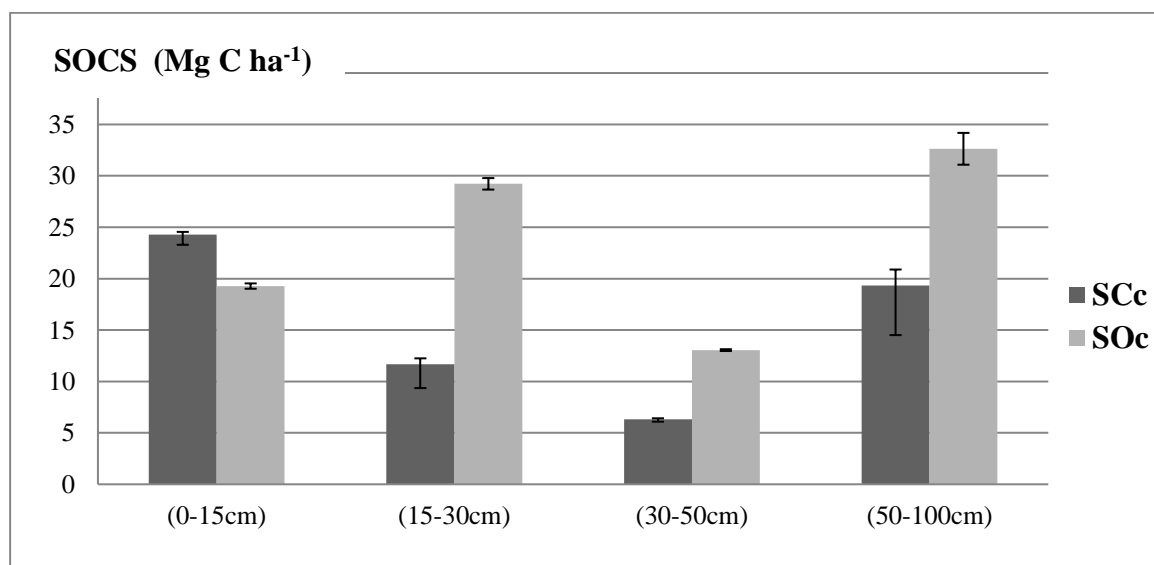


Figure 2. Organic carbon stock of the studied soils according to their occupation.

2. Cumulative CO stock variation. A significant difference ($p < 0.05$) in SCOS for different land use was observed (Figure 3). Akpa et al. (2016) recorded a significant difference between different land use types (forest, scrubland, savannah, grassland and cropland) ranging from $47 \pm 2.356 \text{ Mg C ha}^{-1}$ to $118 \pm 7.984 \text{ Mg C ha}^{-1}$ for Nigerian soils, in contrast to the observations of Minasny et al. (2017) who made the same observation for Tanzanian soils at 30 cm with land use classes (woodland, shrubland, grassland and cropland).

a. Cumulative stock variation for 30 cm. The average SOCS recorded is $48.50 \text{ Mg C ha}^{-1}$ and $35.98 \text{ Mg C ha}^{-1}$ for SOc and SCc respectively. Brahim et al. (2014) found an intermediate value of $41.6 \pm 2.754 \text{ Mg C ha}^{-1}$ in Tunisia at the same depth. For the soil under olive cultivation, the value recorded is higher than that recorded for the soils of the Spanish peninsula (Rodríguez-Murillo, 2001), characterized by the same occupation and depth with $39.9 \pm 2.289 \text{ Mg C ha}^{-1}$ and only 30 Mg C ha^{-1} for French soils (Arrouays, 2008). The lowest value ($35.98 \pm 1.563 \text{ Mg C ha}^{-1}$) concerned citrus cultivation. This value is still higher than that recorded for soils in arid regions of Australia with only $10 \pm 0.974 \text{ Mg C ha}^{-1}$ (Luo et al., 2010) and lower than that recorded by Benouadah et al. (2023) with $46.15 \pm 3.834 \text{ Mg C ha}^{-1}$ in the same study region for a soil under irrigation. For both species studied, citrus represents the least storable land use. This could be mainly explained by the crop management method. These values are lower than those recorded for Spanish soils at the same depth with $50.8 \pm 5.435 \text{ Mg C ha}^{-1}$ (Rodríguez-Murillo, 2001), and for French arable land with $51 \pm 4.982 \text{ Mg C ha}^{-1}$ (Arrouays, 2008), and higher than the value recorded by Brahim et al. (2014) at the same depth for all Tunisian soils with an average of $26.12 \pm 2.574 \text{ Mg C ha}^{-1}$, but remains lower than the global average value for wooded areas with $66.84 \pm 6.854 \text{ Mg C ha}^{-1}$. Our results contradict those of (Arrouays, 2008) which reveal that vines and orchards would store less CO with $30 \pm 2.398 \text{ Mg C ha}^{-1}$ and $50 \pm 5.876 \text{ Mg C ha}^{-1}$ for arable land.

b. Cumulative stock variation for 50 cm. The SOCS recorded is $61.55 \text{ Mg C ha}^{-1}$ for SOc and $42.31 \text{ Mg C ha}^{-1}$ for SCc. These values are intermediate to those recorded for soils in southern Spain for the same soil type and a depth of 50 cm, with $46.2 \pm 2.546 \text{ Mg C ha}^{-1}$ for herbaceous vegetation and higher than those recorded ($35.9 \pm 10.09 \text{ Mg C ha}^{-1}$) for arable land (Munoz-Rojas et al., 2012). Olive cultivation allows the best CO storage.

c. Cumulative stock variation for 100 cm. The results obtained (Figure 4) indicated that the total organic carbon stock (0-100 cm) is $94.18 \text{ Mg C ha}^{-1}$ and $61.65 \text{ Mg C ha}^{-1}$ for SOc and SCc, respectively. Boulmane et al. (2013) found an intermediate value for soils of the Moroccan Middle Atlas ($70 \pm 3.213 \text{ Mg C ha}^{-1}$). On the 0-100 cm layer, the SOC stock under

arboriculture is $129.2 \pm 2.90 \text{ Mg C ha}^{-1}$ (Bounouara et al., 2017). The percentages of SOC in the deep layer ranging from 50 to 100 cm of the total soil stock highlight the importance of the depth parameter in storage since 33% of the CO stored in the soils studied resides in this layer, this observation was confirmed by Jaouadi et al. (2019) for deep soil layers under a semi-arid Mediterranean climate, according to these authors, the rooting of crops would strongly contribute to these high SCOS values in the subsoil. In addition to the high temperature and the unavailability of nutrients for microorganisms in the subsoil layers limiting the degradation of stored CO, other authors have explained this high content by the migration of SCOS to deeper layers by leaching (Benslimane et al., 2023). Balesdent et al. (2017) explained this vertical distribution of carbon by two independent phenomena: (i) the progressive transport of carbon to depth by bioturbation, leaching or leaching, (ii) the in situ biodegradation of new C, slower at depth than at the surface.

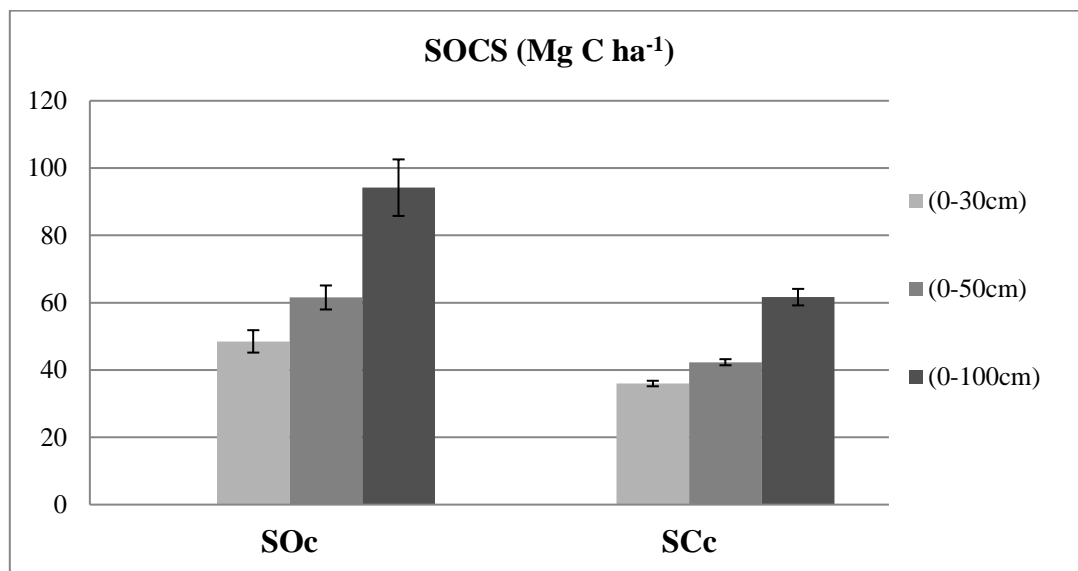


Figure 4. Cumulative stock of CO variation of the studied soils.

3. OC stock variation according to the soil layers (depths). The SCOS varies significantly ($p < 0.05$) between the different studied soil layers (Figure 5). Indeed, Benouadah et al. (2023) report that the distribution of SOCS is likely to vary depending on the depth and the types of crop.

a. OC stock variation for the 0-15cm soil layer. This layer contains on average 20.47% and 39.63% of stored OC according to the land use for the SOc and the SCc respectively. The highest stock is $24.29 \pm 0.259 \text{ Mg C ha}^{-1}$, recorded in citrus cultivation.

b. OC stock variation for the 15-30cm soil layer. According to land use, the highest stock was recorded under olive cultivation ($29.22 \pm 2.331 \text{ Mg C ha}^{-1}$), representing 31.02% of the CO stored in this layer according to land use. Under citrus cultivation, the recorded value

is $11.69 \pm 0.559 \text{ Mg C ha}^{-1}$, the latter representing 18.96% of the CO stored. Almost similar results were found by Benslimane et al. (2023) in the Sidi Bel Abbès region for a soil under olive cultivation at the same layer ($27.63 \pm 3.596 \text{ Mg C ha}^{-1}$).

c. OC stock variation for the 30-50cm soil layer. Depending on land use, this layer contains 10.27% and 13.86% of the CO stored for SCc and SOc respectively, so it represents the lowest stocks $6.33 \pm 0.088 \text{ Mg C ha}^{-1}$ for citrus cultivation and $13.05 \pm 0.240 \text{ Mg C ha}^{-1}$ for olive cultivation.

d. OC stock variation for the 50-100cm soil layer. The highest stock ($32.63 \pm 4.829 \text{ Mg C ha}^{-1}$) was recorded in olive cultivation, representing 34.65% of the CO stored for this layer according to land use. The rate recorded in citrus cultivation is $19.34 \pm 1.547 \text{ Mg C ha}^{-1}$, corresponding to 31.37% of CO stored. The variation in CO distribution according to soil layer (depth) could be explained by the difference in distribution and depth of roots that control CO storage and stabilization (Poirier et al., 2018), also by root inputs at different depths of the soil profile and even by CO leaching from deep layers (Benouadah et al., 2023). For olive cultivation, the highest stock is recorded in the deep layer (50-100cm), followed by the intermediate layer (15-30cm), with 34.65% and 31.02% respectively. This could be due to the fact that the surface profile is the most exposed to natural (erosion) and anthropogenic (plowing) disturbances, which would facilitate the decomposition of organic matter and its release in the form of carbon dioxide emissions (Derrien et al., 2016). Unlike the subsurface layers, which are conditioned by specific processes regulating the storage of organic carbon, however, the mechanisms delaying the decomposition of organic matter in the subsurface layers require further research (Benslimane et al., 2023). According to Balesdent et al. (2017), carbon accumulation in the deepest horizons is more dependent on the soil type than on the crop itself. Indeed, the work of Mathieu et al. (2015) showed at the global level that the degree of stabilization (age) of deep carbon is more dependent on soil type than on climate or land use. The variation can also be explained by factors other than the distribution of carbon restitution or rooting. For citrus cultivation, the highest stock is recorded in the surface layer (0-15cm) followed by the deep layer (50-100cm), with 39.40% and 37.37% respectively. This could be explained by the superficial root system of citrus fruits, which is located in the 1st meter of depth but can extend up to 6 m laterally and which only penetrate the soil to 60 cm of depth (Balesdent et al., 2017), which explains the high sensitivity of citrus fruits to drought, with the exception of the *Poncirus* genus which has a deep taproot system. According to Sow et al. (2024), agroforestry in various ecological systems has significant

potential for soil carbon sequestration compared to monocropping systems in the deep soil layers near the tree than in those far from it. Knowing that, the management of the system and climatic conditions influence the rate and quantity of carbon sequestration. For this reason, agroforestry has gained increased attention as a strategy to sequester carbon (C) and mitigate global climate change. Therefore, it has been recognized as having the greatest potential for C sequestration of all the land uses analyzed in the Land-Use, Land-Use Change and Forestry report of the IPCC (Abbas et al., 2017).

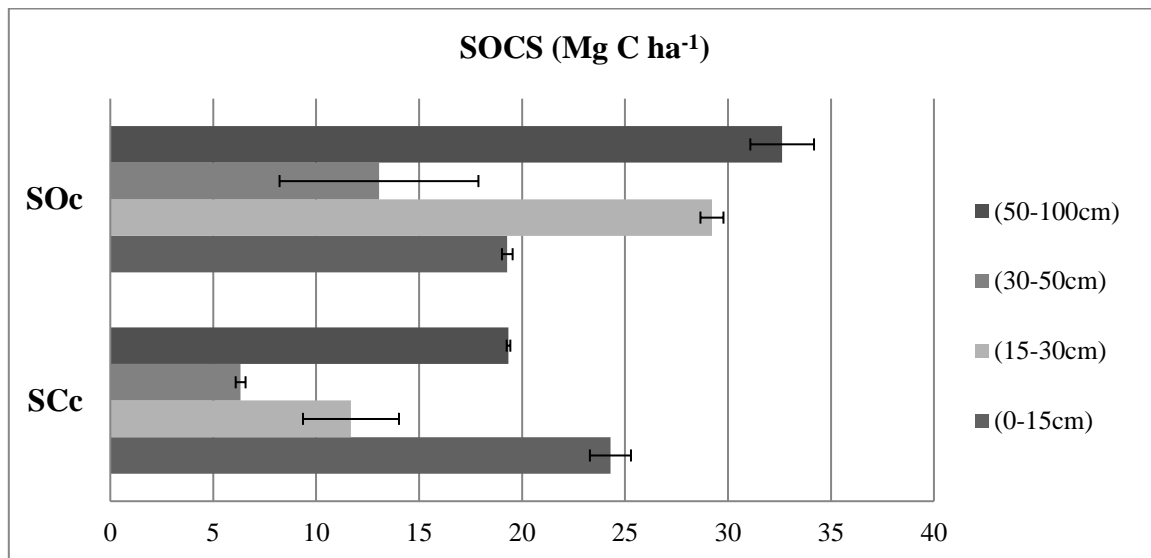


Figure 5. Vertical distribution of organic carbon stock of the studied soils.

Conclusion

In conclusion, we demonstrated that the carbon sequestration in agricultural soils under arboriculture, especially in Mediterranean semi-arid conditions, is strongly influenced by various factors, including land cover, cultivation practices, soil depth and soil physicochemical parameters. The observed variations in soil organic carbon stock (SOCS) between different land use types demonstrate the importance of these factors in managing and preserving soil fertility.

In this study, citrus and olive cultivation showed different carbon sequestration profiles, especially regarding root systems. Citrus cultivation, characterized by trees with relatively shallow and extensive root systems, showed a significant capacity to store organic carbon in the surface soil layers, with the highest carbon stock (24.29 ± 0.259 Mg C ha⁻¹) recorded in the 0-15 cm layer. In contrast, olive cultivation, with trees with deeper and more concentrated root systems, demonstrated a higher capacity to store carbon in the deeper soil layers, with the highest carbon stock (32.63 ± 4.829 Mg C ha⁻¹) recorded in the 50-100 cm layer.

These differences in the root system influence how both crops contribute to soil organic matter formation and carbon sequestration. Organic inputs and root decomposition also differ between citrus and olive cultivation, which may explain the observed variations in carbon storage between the two systems, thus land use influences the SOC stock at surface and depth. Furthermore, the results highlight the importance of soil physicochemical parameters, such as pH and texture, in carbon sequestration. A positive correlation was observed between soil organic carbon stock and silt, while a negative correlation was found with pH. These parameters play a crucial role in regulating soil biological activity and nutrient assimilation, highlighting the importance of maintaining optimal conditions to promote carbon sequestration.

This study highlights the importance of considering these factors, including differences in root systems and carbon storage depths, in agricultural land management to promote carbon sequestration and contribute to climate change mitigation.

It is recommended to carry out the soil microbiological analyses in order to better understand the mechanisms of decomposition of organic matter and storage of organic carbon according to the length of living roots and at different depths (0-15 cm, 15-30 cm, 30-50 cm, 50-100 cm). However, further research is provided to better understand and create awareness about carbon sequestration especially in agroforestry systems as it is recognized as the best sequestration potential and not only soil under arboriculture.

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