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Assessment of soil organic carbon stock in pistachio orchards established under semi-arid climates of Siirt province, Türkiye

Siirt ili yarı kurak iklim koşullarında tesis edilen fıstık bahçelerinde toprak organik karbon stokunun değerlendirilmesi

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ABSTRACT

The management of agricultural lands plays a crucial role in the global carbon (C) cycle. Intensive soil tillage is one of the primary factors contributing to the mineralization of soil organic carbon (SOC), leading to its release into the atmosphere as CO_2. This study determined the soil organic carbon stock (SOCS) in pistachio-growing areas, which have expanded significantly in recent years in Kurtalan district, Siirt province. Spatial variation of SOCS was also mapped within the study area to ensure its long-term monitoring over time. For this purpose, soil samples were collected from a depth of 0–20 cm in 72 pistachio orchards. The soil organic C (SOC) content and bulk density (Bd) of the collected soil samples were determined, and SOCS values were calculated to generate spatial distribution maps. The SOC content ranged from 2.85 g kg^{-1} to 26 g kg^{-1}, while SOCS varied between 8.97 t ha^{-1} and 73.74 t ha^{-1}. Significant variability in SOC and SOCS was observed among soil samples belonging to different texture groups. Additionally, SOC and SOCS values significantly decreased as orchard age increased. The SOC and SOCS values decreased by 20.3% and 22.7%, respectively in pistachio orchards older than 20 years compared 5 years old or younger orchards. This decline in SOC content was also reflected in the SOC:Clay ratio, a key indicator of soil structure stability, which dropped from an average of 0.32 in younger orchards to 0.20 in older orchards. This suggests that agricultural practices in pistachio orchards disrupt soil aggregation, accelerating organic C mineralization and reducing the soil's ability to retain organic matter over time. These results show the urgent need for sustainable soil management strategies to preserve soil integrity, enhance C retention, and support long-term agricultural sustainability in semi-arid pistachio cultivation areas.

Key Words: Soil Organic Carbon, Sustainable Soil Management, Spatial Distribution, Pistachio Orchard

ÖZ

Tarım arazilerinin yönetimi, küresel karbon (C) döngüsünde çok önemli bir rol oynamaktadır. Yoğun toprak işleme, toprak organik karbonunun (SOC) mineralizasyonunu artıran ve CO_2 olarak atmosfere salınmasına yol açan başlıca faktörlerden biridir. Bu çalışmada son dönemlerde Siirt iline bağlı Kurtalan ilçesinde yetiştiriciliği önemli oranda artan Siirt Fıstık bahçelerinde toprak organik C stoku (TOCS)'nun belirlenmesi ve yersel değişimlerinin haritalanarak izlenebilirliğinin sağlanması amaçlanmıştır. Bu amaçla, 72 farklı fıstık bahçesinden 0-20 cm derinlikten toprak örnekleri alınmıştır. Alınan toprak örneklerinin toprak organik C (TOC) içeriği ve hacim ağırlığı belirlenerek TOCS değerleri hesaplanmış ve yersel değişimleri haritalanmıştır. TOC içeriği 2.85 g kg^{-1} ile 26 g kg^{-1} arasında değişirken, SOCS değerleri 8.97 t ha^{-1} ile 73.74 t ha^{-1} arasında değişmiştir. Çalışma alanındaki farklı tekstür gruplarına ait toprak örnekleri arasında TOC ve TOCS değerlerinde önemli düzeyde değişkenlik gözlenmiştir. Ayrıca, meyve bahçesi yaşı arttıkça, SOC ve SOCS değerleri önemli ölçüde azalmıştır. 20 yaş ve üzeri Siirtfıstığı bahçelerinde TOC ve TOCS değerleri 5 yaş ve altı bahçelere göre sırası ile %20.3 ve %22.7 oranında azalmıştır. TOC içeriğindeki bu düşüş, toprak agregat stabilitesinin önemli bir göstergesi olan SOC:Kil oranına da yansımış ve genç bahçelerde ortalama 0.32 iken yaşlı bahçelerde 0.20'ye düşmüştür. Bu durum, Siirtfıstığı bahçelerindeki tarımsal uygulamaların toprak agregasyonunu bozarak organik karbon mineralizasyonunu hızlandırdığını ve toprağın zaman içinde organik madde tutma kabiliyetini azalttığını göstermektedir. Bu sonuçlar, yarı kurak iklime sahip Siirtfıstığı ekim alanlarında toprak bütünlüğünü korumak, karbon tutma oranını artırmak ve uzun vadeli tarımsal sürdürülebilirliği desteklemek için sürdürülebilir toprak yönetimi stratejilerine acil ihtiyaç olduğunu göstermektedir.

Anahtar Kelimeler: Toprak Organik Karbonu, Sürdürülebilir Toprak Yönetimi, Yersel Değişim, Siirt Fıstık Bahçeleri

Introduction

Soil organic carbon (SOC) is a fundamental component for the sustainability of agricultural ecosystems. The SOC plays a role in processes related to climate change by affecting the carbon cycle in the atmosphere (Yadav et al., 2017). Similarly, it is critically important in regulating nutrient and water cycles in the soil, as well as creating habitats for biodiversity (Padarian et al., 2022). The SOC also plays a significant role in increasing agricultural productivity by enhancing soil aggregate stability, increasing erosion resistance, regulating bulk density, improving water retention capacity to reduce drought stress, and supporting soil health by promoting microbial activity (Ahmad et al., 2025; Chowdhury et al., 2021; Francaviglia et al., 2023).

The SOC represents ~70-75% of the terrestrial carbon pool, meaning that even small changes in this pool can lead to significant and widespread impacts on the global carbon cycle (Muñoz-Rojas et al., 2017). In this context, the accumulation of SOC in the soil and its ability to maintain stability over long periods are crucial for combating climate change and ensuring the sustainability of soil health. The accumulation of SOC significantly varies depending on land use and the soil management strategies (Beillouin et al., 2022; Lessmann et al., 2022). Human activities such as deforestation, intensive tillage, inadequate crop rotation, excessive use of fertilizers and pesticides, and biomass burning lead to losses in the SOC pool (released into the atmosphere), which negatively impacts soil fertility and disrupts the ecosystem services provided by terrestrial ecosystems (Abdulkadir et al., 2021; Adekiya et al., 2023; Kumar et al., 2020).

Approximately 11-30% of anthropogenic greenhouse gas emissions originate from agricultural lands (Acosta et al., 2024). The primary sources of CO_2 emissions from agricultural lands are excessive soil tillage and the use of fossil fuels in agricultural machinery (Sørensen et al., 2014; Hussain et al., 2021). Microbial activities occurring in the soil are the main source of CO_2 production, and the release of greenhouse gases into the atmosphere is directly related to factors such as soil pore volume, moisture content, and aggregation. Traditional tillage methods disrupt soil structure, leading to significant changes in moisture and temperature conditions. These changes, particularly the reduction of soil moisture and the formation of oxygen-rich environments, create conditions for the rapid decomposition of organic matter by microorganisms. As a result, SOC is converted to CO_2 and released into the atmosphere (de Oliveira Silva et al., 2019).

The role of SOC in determining soil structure and workability has gained increasing attention, particularly in relation to its balance with clay content. The SOC:clay ratio, proposed by Johannes et al. (2017), serves as a key criterion for assessing soil physical quality. This ratio helps determine whether the SOC content is sufficient relative to the clay fraction, classifying soil structural conditions based on threshold values. In light of these processes, this study focuses on the semi-arid region of Kurtalan, Siirt, where intensive soil tillage is prevalent in pistachio orchards. The objective is to assess the SOC, SOCS levels and OC:Clay ratio and map their spatial variation within these orchards, as such practices may significantly influence the carbon dynamics and sustainability of the soil. Mapping these variations could provide critical insights into how soil management strategies in this region affect SOC stocks and contribute to broader understanding of carbon sequestration potential in semi-arid agricultural landscapes. Additionally, given its potential as an indicator of soil health and sustainable land management, this study considers the SOC:clay ratio as a key criterion for evaluating the effects of pistachio orchard age on soil degradation and identifying strategies for improving soil structure.

Material and Methods

Study Area

The study area encompasses ~2208 ha of pistachio orchards located in the Kurtalan district of Siirt province, between the coordinates 37˚52'48" - 37˚57'53" north latitude and 41˚26'59" - 41˚35'18" east longitude (Figure 1). Situated in the southeastern region of Türkiye, the study area exhibits a transitional climate between the continental and Mediterranean climates, with an average elevation of 1125 meters above sea level. The surrounding terrain is mountainous, with less rugged areas in the southern parts, and these geographical characteristics significantly influence the region's climatic conditions. The long-term average annual precipitation in the area is 572.9 mm, with a relative humidity of 52.8% and a mean temperature of 17.5°C (Karaman and Turan, 2019). Geologically, the region is underlain by the Germik and Şelmo formations (Yeşilova and Helvacı, 2013). The Germik formation is primarily composed of gypsum, anhydrite, dolomite, and limestone, while the Şelmo formation consists of continental sediments, which are believed to have originated in an ancient lake or sea basin.

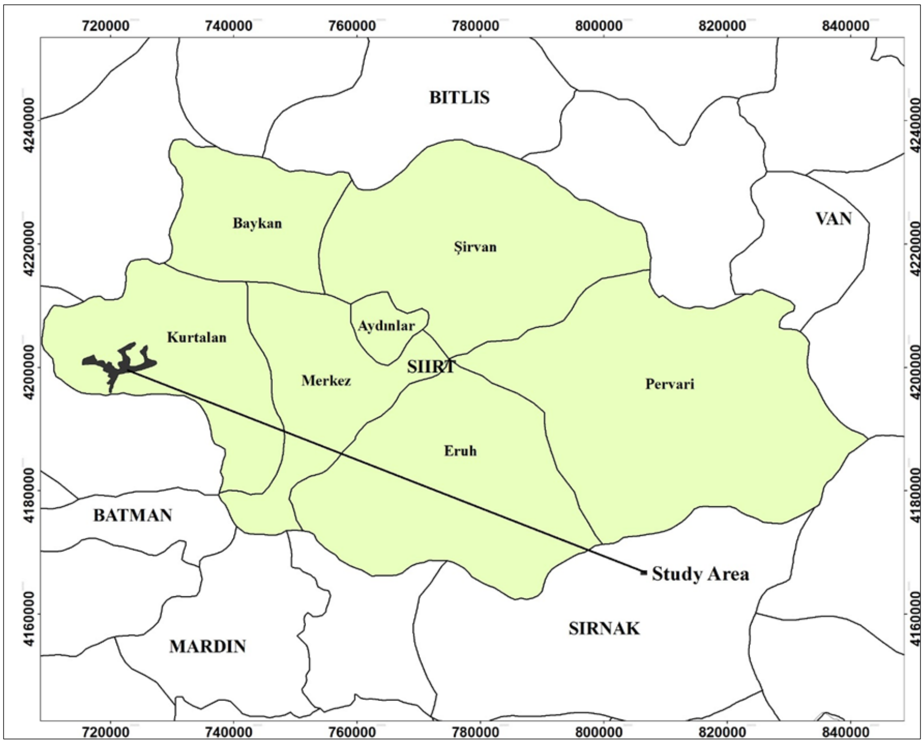

Figure 1. Location of study area

Soil Sampling

To assess the carbon storage potential of soils in pistachio orchards located in the Kurtalan district of Siirt province, soil samples (disturbed and undisturbed) were collected from 72 orchards (Figure 2) at a depth of 0–20 cm using a random sampling method. Undisturbed soil samples were collected using two 100 cm³ steel cylinders from each sampling point. In each orchard, disturbed soil samples were taken from four different points, combined in a container, thoroughly mixed, and approximately 1 kg of the composite sample was brought to the laboratory for analysis. Immediately after collection, disturbed samples were placed in airtight polyethylene bags and undisturbed cores in steel cylinders were wrapped with parafilm to preserve structure and moisture.

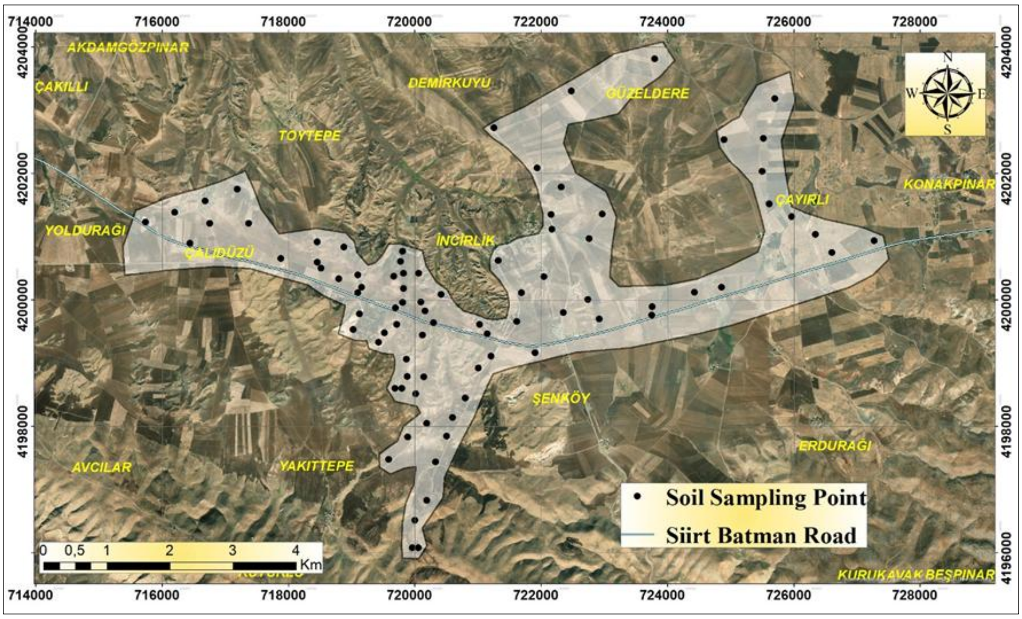

Figure 2. Soil sampling locations in the study area

Soil Analysis

Disturbed soil samples were air-dried at room temperature and sieved through a 2 mm mesh for laboratory analyses. The clay content was determined using the hydrometer method (Bouyocous, 1962), soil organic carbon (SOC) was determined using the modified Walkley-Black method (Nelson and Sommers, 1982), while bulk density (BD) was measured in undisturbed soil samples following the cylinder method (Blake & Hartge, 1986).

Following the determination of SOC content and BD in the study area, the soil organic carbon stock (SOCS) for each sampling point was calculated using Equation 1 (Zhang et al., 2013).

$$SOCS = BD\ x\ D\ x\ SOC\ x\ A \quad \text{……………………………}1$$

In this equation, BD represents the bulk density of the soil (Mg m^{-3}), D denotes the depth at which the soil sample was collected (meters), SOC refers to the SOC content (g kg^{-1}) determined using the Walkley-Black method, and A represents the total coverage of the study area (ha: 10^4 m^2).

The SOC:clay ratio was used to evaluate the relationship between SOC and clay content. Following the criteria proposed by Johannes et al. (2017), soils with an SOC:clay ratio above 1:8 were classified as "very well-structured," those between 1:10 and 1:8 as "well-structured," those between 1:13 and 1:10 as requiring "structural improvement," and those below 1:13 as "degraded." To assess these classifications, soil samples were analyzed in the laboratory, and the SOC:clay ratio was calculated for each sample. However, the SOC:Clay ratio may not be sensitive enough to detect changes in SOC due to management practices, particularly in high-clay soils where SOC is more stable. To address these limitations, Poeplau and Don (2023) proposed the SOC:SOCexp ratio, which compares measured SOC to an expected value derived from a regression with clay content. This method accounts for the natural variation in SOC across soil types, providing a more context-sensitive assessment of SOC dynamics. Unlike the SOC:Clay ratio, the SOC:SOCexp ratio is less prone to extreme biases and better aligns with soil structural properties such as porosity and bulk density.

Statistical Analysis and Spatial Distribution of Soil Samples

Descriptive statistics for the SOC, BD, SOCS, and SOC:clay content were calculated using the SPSS 21.0 software. Spatial distributions were modeled using the GS+ 7.0 software, and the most suitable model parameters (sill, nugget, range) were utilized to generate spatial distribution maps in ArcGIS 10.2. Selection of the most appropriate model was based on its ability to best describe spatial variability as a function of distance while constructing semivariograms for SOC, BD, and SOCS values. Coefficient of determination (R^2) and the residual sum of squares (RSS) indicating measurement errors, were considered as key criteria in this selection process. The optimal model was identified based on the highest possible R^2 value, approaching 1.0, and the lowest RSS value, approaching zero (Chang and Lin, 2000).

Results and Discussion

Descriptive Statistics of Soil Properties

The bulk density ranged between 1.16 and 1.74 g cm^{-3}, with a mean value of 1.45 g cm^{-3} (Table 1). Bulk density can significantly vary depending on soil organic matter content, texture, aggregation, and pore structure of soils (Chaudhari et al., 2013). Although the coefficient of variability (CV) value of 8.35% indicates a relatively narrow range of variation, the minimum and maximum bulk density values suggest significant differences in soil compaction. Bulk density was low enough to pose no risk in some areas, while it was high enough to potentially hinder root development and plant growth in other areas. The variability in bulk density within the study area can be attributed to soil texture, organic matter content, and stoniness. Additionally, differences in soil management practices play a significant role; while some orchards undergo soil tillage at least six to eight times per year, others experience little to no tillage, contributing to the observed variations. Clay content varies between 10% and 62.5% and sand content ranges from 17.1% to 75%. The high variability in clay (CV = 26.2%) and sand content (CV = 38%) (Budak et al., 2025) is a key factor contributing to the variation in bulk density.

The frequency of soil tillage operations, coupled with the diversity of implements used (such as plows, cultivators, and disc harrows), plays a crucial role in modulating soil bulk density. In this context, Fallahzade et al. (2020) demonstrated that traditional tillage methods markedly reduce surface soil bulk density in pistachio orchards in Iran. Complementing these findings, Salem et al. (2015) observed that conventional tillage practices lead to a significantly greater decline in bulk density compared to more conservative approaches, such as reduced or no-till systems. Moreover, Topa et al. (2021) revealed that the long-term impacts of tillage are depth-dependent; while the surface layer (0-10 cm) experiences a reduction in bulk density, deeper soil layers exhibit a significant increase.

The skewness and kurtosis values provide insight into the distributional characteristics of the soil parameters measured. For SOC and SOCS, the skewness values of 0.73 and 0.77, respectively, indicate a moderate positive skew. This suggests that both datasets have a slight asymmetry, with a tendency for a longer right tail, which may reflect the presence of higher value outliers or a clustering of lower values. In addition, the kurtosis values for SOC (1.07) and SOCS (1.05) imply that these distributions are moderately leptokurtic, meaning they are somewhat more peaked with heavier tails than a normal distribution. This characteristic can have implications for statistical analyses, as it suggests a higher probability of extreme values compared to a mesokurtic (normal) distribution (Hayes et al., 2022). In contrast, skewness (0.22) and kurtosis (-0.03) of BD indicate a distribution that is nearly symmetrical and close to normal in terms of tail weight and peakedness.

Table 1. Descriptive statistics of soil organic carbon, bulk density, soc/clay and soil organic carbon stocks (0-20 cm)

		Minimum	Maximum	Mean	Standard Dev.	CV*	Kurtosis	Skewness
SOC	g kg^{-1}	2.85	26.00	10.92	4.22	38.6	1.07	0.73
BD	g cm^{-3}	1.16	1.74	1.45	0.12	8.4	-0.03	0.22
SOC:Clay		0.07	0.86	0.27	0.14	50.59	4.35	1.70
SOCS	t ha^{-1}	8.97	73.74	31.28	11.75	37.6	1.05	0.77

*Coefficient of variability (%)

The SOC is a critical component of the global carbon cycle, functioning both as a source and a sink of atmospheric CO_2. As a major reservoir in terrestrial ecosystems, SOC plays a pivotal role in regulating carbon fluxes between the soil and the atmosphere. The mineralization of plant and animal residues represents a fundamental process in the carbon cycle, directly influencing the SOC pool. This decomposition process is driven by microbial activity, which breaks down organic matter into simpler compounds, releasing CO_2 into the atmosphere (Xu et al., 2023). In intensively managed agricultural systems as in pistachio orchards, soil disturbances such as plowing contribute to the breakdown of macroaggregates, which are crucial for stabilizing organic carbon. The disruption of these aggregates exposes previously protected SOC to microbial degradation, leading to its conversion into CO_2 and subsequent release into the atmosphere. Consequently, the loss of SOC is accelerated, reducing soil fertility and diminishing the soil's capacity to act as a carbon sink (Wang et al., 2019). The extent of SOC depletion depends on the intensity and frequency of soil disturbances, indicating the importance of sustainable land management practices in mitigating carbon losses.

Relationship between orchard age and carbon storage potential of soils

A one-way analysis of variance (ANOVA) was performed to determine whether SOC, SOCS, and OC:Clay ratio exhibited statistically significant variations across pistachio orchards of different age groups (Table 2). The results indicated that the mean SOC and SOCS values did not differ significantly among orchard age groups ($p > 0.05$). However, the OC:Clay ratio showed a statistically significant variation across age groups ($p < 0.05$). Although no statistically significant change was observed according to orchard age, the average SOC (%20.37) and SOCS (%22.76) values in the soils of 5-year-old and 20-year-old orchards significantly decreased with increasing orchard age. This difference was particularly pronounced between young orchards (≤ 5 years old) and mature orchards (≥ 20 years old), suggesting that soil organic matter stabilization mechanisms may vary with orchard development. The observed variation could be attributed to differences in root system maturity, microbial activity, organic matter decomposition rates, and soil structural evolution over time. These findings highlight the necessity of age-specific soil management strategies to optimize carbon sequestration and maintain long-term soil health and productivity in pistachio orchards

Orchards, as long-term perennial agricultural systems, play a significant role in SOC sequestration. Unlike annual cropping systems, which involve frequent soil disturbances, orchards are typically managed with minimal soil disruption, allowing for greater SOC accumulation and stabilization. The presence of deep-rooted perennial trees contributes to enhanced carbon inputs through continuous leaf litter deposition, root exudates, and organic matter incorporation into the soil profile (Montanaro et al., 2017). In traditional pistachio orchards, where intensive soil tillage is commonly practiced, SOC content varies between 2.85 g kg^{-1} and 26 g kg^{-1}, with an average value of 10.92 g kg^{-1} (Table 1). When classified based on orchard age, a clear trend of declining SOC content with increasing orchard age is observed (Table 2). Specifically, in young orchards aged 1–5 years, the average SOC content is 11.83 g kg^{-1}, whereas in older orchards exceeding 20 years, this value declines to 9.42 g kg^{-1}. This pattern suggests that intensive soil disturbance in pistachio orchards accelerates SOC depletion over time, counteracting the expected accumulation of organic carbon in perennial systems. Soil aggregates play a crucial role in restricting the access of microorganisms, enzymes, and oxygen to organic compounds, thereby slowing down the mineralization of organic carbon. This physical protection mechanism helps maintain higher SOC levels over time (Topa et al., 2021). Unlike well-managed perennial orchards, where undisturbed soils promote stable macroaggregate formation and protect SOC from oxidation (Cao et al., 2021), frequent tillage in pistachio orchards disrupts soil structure, exposing SOC to microbial decomposition and increasing its loss as CO_2. The stability of carbon-associated aggregates differs between macroaggregates and microaggregates, affecting their ability to preserve SOC. As macroaggregates gradually break down into smaller microaggregate-sized particles, the rate of mineralization intensifies, leading to greater carbon losses (Jat et al., 2019). Research indicates that soils subjected to minimal tillage or no-till practices tend to develop macroaggregates with a higher capacity for organic carbon storage compared to those undergoing conventional tillage (Zheng et al., 2018). In pistachio orchards, where soil disturbance becomes more frequent as orchard age increases, a significant portion of macroaggregates is broken down. This continuous disruption likely contributes to the decline in SOC, further accelerating carbon depletion in these intensively managed systems.

In the study area, SOCS values range from 8.97 t ha^{-1} to 73.74 t ha^{-1}, with an average of 31.28 t ha^{-1} (Table 1). Similar to SOC content (38.6% CV), SOCS values also exhibit high variability, with a CV of 37.6%, likely due to differences in orchard age and management practices. Research conducted in the Dicle Basin, which has a similar climate, reported that among various land-use types, including croplands, orchards, vegetable fields, grasslands, and forests, the lowest average SOCS values were found in croplands (28.91 t ha^{-1}), followed by fruit orchards (31.97 t ha^{-1}) (Budak and Günal, 2018). These findings shows the relatively lower SOC storage capacity of orchard soils compared to natural ecosystems, emphasizing the impact of land management on carbon sequestration potential. The significantly lower SOCS values recorded in pistachio orchards in the current study, compared to the findings of Budak and Günal (2018), can be primarily attributed to the lack of fertilization (both organic and inorganic) and the frequent soil tillage, which is performed 6 to 8 times per year. These intensive management practices have likely contributed to the depletion of soil organic carbon over time. Additionally, the conversion of lands previously used for intensive wheat and barley cultivation into pistachio orchards has further exacerbated SOC losses. The prolonged history of intensive agricultural production in these areas has led to a substantial reduction in organic carbon levels, ultimately resulting in lower SOCS values. Furthermore, the reduction in SOC accelerates the depletion of plant nutrients and the decline in carbon stocks, thereby adversely affecting soil fertility and potentially destabilizing ecosystem balance. Research has demonstrated that prolonged intensive tillage can reduce SOCS by 20 to 50% (Conant et al., 2007). This phenomenon represents a significant risk factor not only for sustainable agricultural practices but also for the global carbon balance. Öztürk (2025) reported that in pistachio cultivation areas in Şanlıurfa, which has a similar climate, SOC values ranged from 8.12 to 42.69 g kg^{-1}, while SOCS varied between 10.5 and 45.3 Mg ha^{-1}, with these variations generally attributed to differences in land use. In addition, in a study conducted by Yakupoğlu et al. (2017) on the erodibility of soils in areas converted from native shrubland to pistachio orchards, it was reported that the average SOC content in the natural area was 12.96%, while in the pistachio orchards it was 7.30%. The change in SOC values in the same region can be associated with soil tillage and management systems.

The SOC to clay ratio (SOC:Clay) is a widely recognized indicator of soil structural quality, influencing key attributes such as porosity, aggregate stability, and resistance to erosion. This ratio serves as a reliable metric for assessing soil organic matter (SOM) sufficiency, with established threshold values delineating soil structural conditions ranging from very good to degraded (Prout et al., 2021). In this study, the SOC:Clay ratio exhibited a mean of 0.27, with values ranging from 0.07 to 0.86 and a standard deviation of 0.14. The CV was high at 50.59%, indicating substantial variability across the sampled soils. The average SOC:Clay ratio of 0.27 surpasses the threshold of 0.125 (1:8) considered indicative of very good structural quality (Johannes et al., 2017; Prout et al., 2021). This suggests that, on average, the soils in this study exhibit excellent structural conditions, supporting findings that a SOC:Clay ratio above 1:10 (0.10) generally corresponds to stable soil aggregation and improved soil functions (Dexter et al., 2008; Prout et al., 2021). However, despite the high average SOC:Clay ratio, the range of values indicates that some soil samples fall below the critical 0.077 (1:13) threshold, suggesting potential structural degradation (Prout et al., 2021). This is particularly relevant as arable soils and those under lower precipitation conditions with frequent tillage have been found to be more susceptible to SOC depletion, often falling below the 1:13 threshold (Verheijen et al., 2005; Prout et al., 2021). The positive skewness (1.70) and high kurtosis (4.35) observed in this dataset further indicate that while many soils have high SOC:Clay ratios, there is a tail of soils with significantly lower values that may require management interventions to enhance their structural integrity.

Table 2. Soil organic carbon (SOC), soil organic carbon stock (SOCS), and SOC:Clay ratio across different age groups of Siirt pistachio orchards

Orchard Age	SOC	SOCS	SOC:Clay
≤5	11.83[a]	35.45[a]	0.32[a]
6-10	10.9[a]	30.48[a]	0.26[ba]
11-20	10.07[a]	27.77[a]	0.21[ba]
≥20	9.42[a]	27.38[a]	0.20[b]
ANOVA	0.131	0.134	0.045

Studies have demonstrated that the SOC:Clay ratio is a robust predictor of soil structural conditions across various land uses and soil types. In England and Wales, for example, SOC:Clay ratios have been used as a guideline to classify soil conditions, revealing that arable lands frequently exhibit degraded structural quality due to lower SOC retention relative to clay content (Prout et al., 2021). Given this, maintaining SOC:Clay ratios above 1:10 should be an essential soil management goal to prevent degradation and improve soil functionality (Johannes et al., 2017; Prout et al., 2021).

When the SOC:Clay ratio is equal to or greater than 1/8 (0.125), clay minerals effectively protect SOC from decomposition (Sauzet et al., 2024). However, intensive and repeated soil tillage disrupts soil aggregates, leading to their fragmentation into smaller particles. As aggregates break down, organic carbon becomes more exposed to microbial activity, accelerating its decomposition and subsequent loss. This process ultimately results in a decline in the SOC:Clay ratio (Prout et al., 2022). Analysis of SOC:Clay values in relation to orchard age revealed a clear decline in the ratio as orchards matured. In pistachio orchards aged five years or younger, the SOC:Clay ratio averaged 0.32. However, with increasing orchard age, a substantial reduction was observed, aligning with the decreasing trends in SOC and SOCS values and ultimately reaching 0.20. The differences in the OC:Clay ratio according to orchard age were found to be statistically significant (p = 0.045) (Table 2). The approximately 40% decline in the SOC:Clay ratio in orchards aged 20 years and older, compared to their younger counterparts, indicates that the practices in pistachio orchards may contribute to aggregate disruption and accelerate organic carbon mineralization. While the SOC:Clay ratio has been widely used as an indicator of soil structural stability and organic carbon stabilization potential, recent studies have raised concerns about its applicability and reliability. Poeplau and Don (2023) argue that the SOC:Clay ratio is strongly biased towards clay content, leading to an exaggerated classification of fine-textured soils as degraded, while falsely indicating that coarse-textured soils are in good condition. In their analysis of over 2,900 topsoil samples from the German Agricultural Soil Inventory, they found that 94% of Chernozems, soils known for their high fertility and SOC content, were classified as degraded or moderate based on the SOC:Clay ratio. This suggests that the metric does not adequately reflect the true carbon sequestration potential or soil health status.

Spatial Distribution of Soil Organic Carbon in Pistachio Orchards

The spatial distribution maps of SOCS, SOC, and bulk density are presented in Figure 3. The southern and northern sections of the study area contain pistachio orchards with the highest SOCS values, whereas the central regions consist of orchards with the lowest SOCS values (Figure 3). The land between İncirlik Village and Şenköy is primarily composed of 15-year-old and older pistachio orchards, while other areas represent lands that have been converted into pistachio orchards within the last decade. Since SOCS values are calculated using bulk density and SOC content as key factors, their spatial distribution closely mirrors that of SOC (Figure 3). The loss of organic matter critically impairs soil structure, water retention, and nutrient cycling, initiating a cascade of detrimental effects on both soil health and overall ecosystem functionality. Organic matter is essential for maintaining soil aggregation and moisture conservation, and its depletion can exacerbate erosion processes while reducing the soil's capacity to sequester carbon (Lal, 2004). In this context, pistachio orchards with older trees are found to be particularly susceptible to erosion. This increased vulnerability can be attributed to several factors: older trees often exhibit diminished canopy cover and less vigorous root systems, which weakens the soil's protective structure and thereby enhances the likelihood of surface erosion. Furthermore, intensive land management practices that accelerate organic matter loss further compromise soil structural integrity, exacerbating erosion risks and undermining the sustainability of these agroecosystems.

Specifically, the SOC values within the study area exhibit a distinct spatial distribution, with the southern and northern sectors recording the highest values, while the central zone has the lowest. The spatial variation map created for bulk density reveals that the highest values are concentrated along a north–south trending belt between the villages of Şenköy, İncirlik, Demirkuyu, and Güzeldere. In the pistachio orchards located in these areas, the elevated bulk density relative to other orchards can be primarily attributed to the soils' high sand content. Indeed, the spatial variation map for sand content prepared by Budak et al. (2025) clearly indicates that the highest sand content (exceeding 50%) is found within these particular zones. This pronounced sandy nature of the soils is indicative of a historical active fluvial system along this alignment. The observed distribution of SOC may be influenced by several interrelated factors, including variations in vegetation cover, land management practices, and inherent soil properties (Six et al., 2002; Lal, 2004). Soils with high sand content typically exhibit increased bulk density and reduced water retention capacity (Brady and Weil, 2008), conditions that can hinder the stabilization and accumulation of organic matter. Furthermore, the hydrological processes associated with past stream activity likely contributed to the depositional patterns observed in the current soil texture, thereby affecting both SOC distribution and bulk density (Blake and Hartge, 1986). Shangguan et al. (2014) also emphasizes that spatial variability in soil physical properties is often closely linked to both natural processes and anthropogenic impacts, underscoring the complexity of soil dynamics in agricultural landscapes.

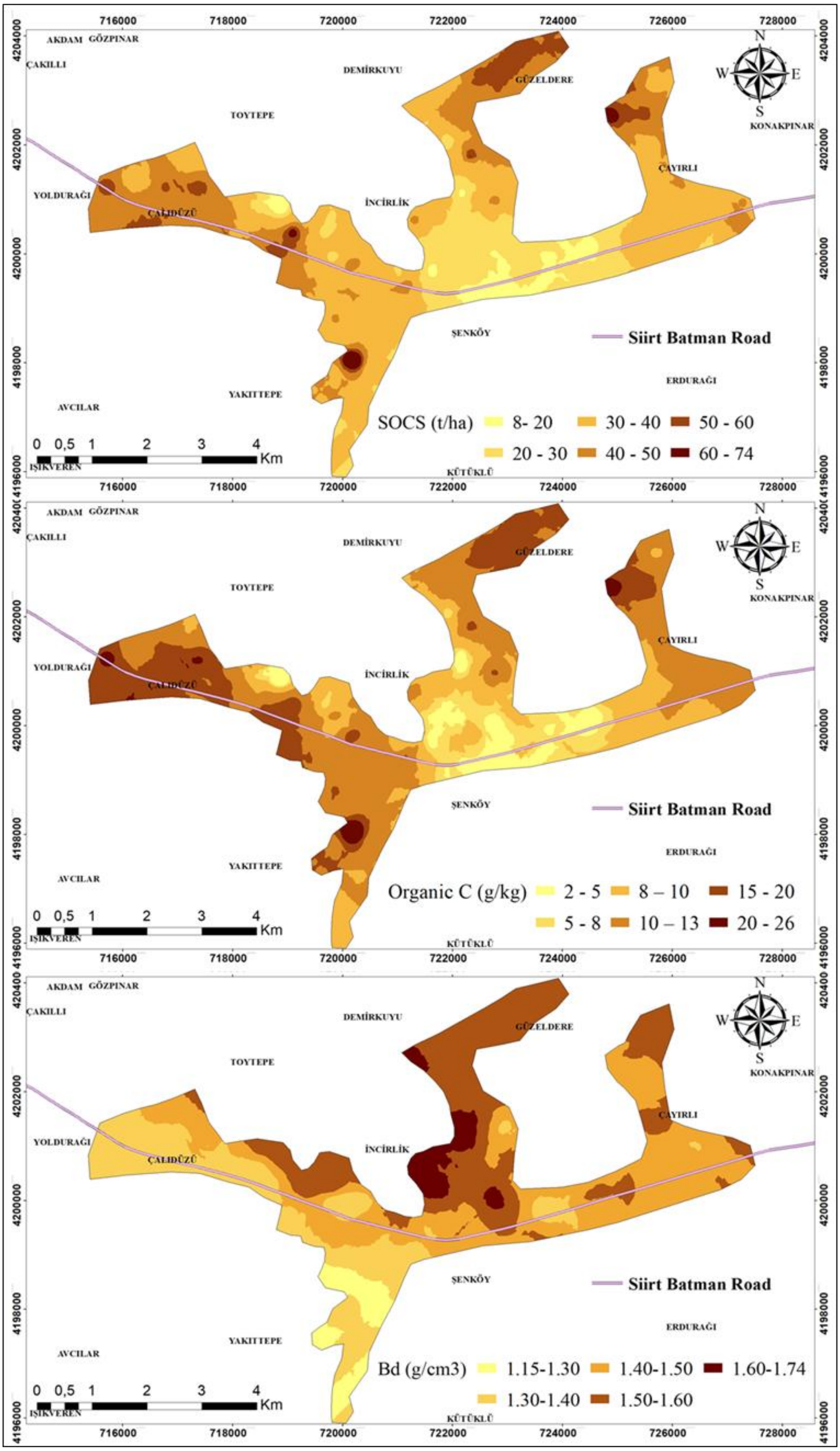

Figure 3. Spatial distribution maps of SOCS, SOC and bulk density values in the study area

Conclusion

The results indicate that the soil management practices applied in the pistachio orchards have led to a significant decrease in both organic carbon and total organic carbon stocks. Intensive tillage, in particular, has accelerated the loss of organic matter, thereby disrupting soil carbon dynamics. Additionally, the sloped nature of the study area has heightened the risk of water erosion, resulting in the loss of nutrient-rich topsoil and a consequent decline in soil fertility. This erosion-driven loss of organic carbon disrupts the intricate relationships between soil, water, and vegetation, which can ultimately reduce agricultural productivity over the long term.

A key indicator of soil structural stability, the SOC:Clay ratio, further reveals the impact of these management practices. The observed decline in SOC:Clay ratios, particularly in older orchards, suggests a progressive reduction in SOC:Clay ratio, which can impair aggregate stability and increase susceptibility to degradation. Since an SOC:Clay ratio below the critical threshold of 1:10 (0.10) is often associated with poor structural quality and reduced carbon sequestration potential, the significant decrease in this ratio across older orchards shows the urgency of adopting sustainable management interventions.

In response to these challenges, it is imperative that sustainable soil management practices be adopted in pistachio orchards established on sloped terrains. Strategies such as reduced tillage, the addition of organic amendments, and the maintenance of vegetative cover are critical for preserving the soil's carbon storage capacity and preventing further erosion in pistachio orchards. Moreover, the spatial variation maps developed in this study provide a valuable framework for monitoring changes in SOCS of pistachio orchards over time, thereby supporting the timely implementation of measures to mitigate soil degradation and ensure the long-term sustainability of pistachio production.

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Conflict of Interest

The authors declare that there is no conflict of interest.

Author Contributions:

Data processing and manuscript preparation were carried out by Mesut Budak, Elif Günal, and Miraç Kılıç. Fieldwork, laboratory analyses, and statistical evaluations were conducted by Kübra Polat, Mesut Sırrı, and Reşat Yolbaş.

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