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Soil Organic Carbon and Carbon Stocks in Calcareous Soils across Different Land Uses and Land Covers

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ABSTRACT

Greenhouse gases contribute to increasing atmospheric temperatures, with carbon dioxide being the most important contributor. One of the most effective approaches for reducing atmospheric carbon dioxide concentrations is its sequestration in soils. This study investigated soil organic carbon (SOC) content and carbon sequestration (CS) at surface (0–15 cm) and subsurface (15–30 cm) depths under different land uses, including forest, agricultural land, and tree plantations, in the Gyan Plain, Hamadan Province, Iran. Soil samples were randomly collected from 48 locations at two depths, and various physical and chemical soil properties were analyzed. CS was calculated for both soil depths. Pearson correlation analysis at the surface depth showed significant negative correlations between SOC and clay plus silt content ($r = -0.33$, $p < 0.01$), while significant positive correlations were observed with cation exchange capacity (CEC) ($r = 0.33$), sand content ($r = 0.32$), saturation moisture content ($r = 0.55$), and total nitrogen ($r = 0.38$). At the subsurface depth, SOC showed a significant negative correlation with clay plus silt content ($r = -0.45$, $p < 0.01$), whereas saturation moisture content ($r = 0.33$) and sand content ($r = 0.50$) showed significant positive correlations with SOC. CS at both surface ($r = -0.59$) and subsurface ($r = -0.63$) depths exhibited significant negative correlations with bulk density ($p < 0.01$) and strong positive correlations with SOC (surface: $r = 0.82$; subsurface: $r = 0.75$; $p < 0.01$). Soil depth significantly affected SOC ($p < 0.01$) but had no significant effect on CS. Mean comparisons indicated that forest land use had the highest SOC values at both depths, while tree plantations showed the highest CS values. Agricultural land use had the lowest SOC and CS values. Among different crop types, canola and maize had the highest mean CS, whereas wheat had the lowest. Overall, conversion of forest land to agricultural land reduced SOC and CS at both depths, and crop type significantly influenced carbon storage. Therefore, implementing appropriate crop rotation strategies in agricultural systems is recommended to reduce SOC losses and enhance soil carbon sequestration.

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1. Introduction

As the human population continues to grow, deforestation rates have also risen due to agricultural expansion, urban growth, infrastructure development, and natural resource extraction. Consequently, forest lands are being converted into agricultural and urban areas (FAO, 2016). Since reducing atmospheric carbon dioxide concentrations through industrial methods, such as filtration, is costly and impractical on a large scale, the urgent and fundamental need to lower carbon dioxide levels can be addressed more effectively through affordable technologies, such as sequestration by plants. Soils store twice as much carbon as the atmosphere, playing a crucial role in global carbon cycles (Deng *et al.*, 2016). Atmospheric carbon dioxide is absorbed by plants, trees, and grasses through the process of photosynthesis and subsequently stored in the roots, foliage, trunks, and branches of trees (Debbarma, 2012). The influence of land use on stabilizing carbon dioxide levels and enhancing soil carbon storage potential has garnered significant attention in recent years (Wang *et al.*, 2016; Hammad *et al.*, 2020; Calvo de Anta, *et al.*, 2020; Meena *et al.*, 2024). Understanding the relationships between soil organic carbon (SOC), land use, and land cover provides valuable insights for predicting the impacts of land use and land cover changes on soil organic carbon stocks. Additionally, this knowledge can inform the development of policies and management strategies aimed at reducing greenhouse gas emissions (Munoz-Rojas *et al.*, 2012). Sperow (2016) argues that the accumulation of SOC in cropland depends on management practices that minimize soil disturbance, maximize crop residue protection, and optimize the efficient use of water and nutrients. Studies worldwide indicate that SOC decreases by 20–43% when natural forests or perennial grasslands are converted to agricultural land (Deng *et al.*, 2016). Results have shown that carbon stocks in the topsoil of agricultural systems are lower compared to adjacent primary forests in the Amazon, primarily due to reduced input of biomass residues (Wang *et al.*, 2016). Soil carbon storage is not only dependent on the surface layer but is also influenced by soil profile depth. For example, more than 50% of the inorganic and organic carbon stored within the top one meter of soil is concentrated in the upper 30 cm (Lal *et al.*, 2015; Olson and Al-Kiasi; 2015; Akpa *et al.*, 2016; Calvo de Anta, *et al.*, 2020). The researchers found that pH (Wang *et al.*, 2016; Calvo de Anta, *et al.*, 2020), Bulk density (Wang *et al.*, 2016), lime content (Calvo de Anta, *et al.*, 2020), cover crops (Hammad *et al.*, 2020), elevation and soil moisture (Chen *et al.*, 2023) and nitrogen (Deng *et al.*, 2016) were the most important factors affecting soil organic carbon levels. Conservation of SOC also depends on soil texture, with studies showing that clay soils retain more carbon than sandy soils under the same environmental conditions (Lal *et al.*, 2015). Additionally, research has found that alternating strip cropping of legumes in fine-textured soils sequesters more carbon than in coarse-textured soils (Sperow, 2016). However, conversion from forest to pasture may increase net organic carbon due to higher carbon and nitrogen stocks, greater soil microbial biomass, and a lower respiration coefficient, leading to net carbon sequestration (CS) in the soil. According to a study, SOC is stored under forests (48%), followed by shrubs (20%) and agricultural lands (18%) (Calvo de Anta *et al.*, 2020). Meena *et al.* (2024) studied six different land uses in India and found that forest land had the highest total soil organic carbon content, while wasteland had the lowest carbon content across all components. The highest carbon instability index was also statistically significant only in forest land use. Chen *et al.* (2023) demonstrated that various factors influence SOC storage, with altitude having an indirect effect and rainfall a direct effect. Agricultural lands exhibiting high SOC storage were primarily located in low-elevation, water-scarce regions. Tikuye *et al.* (2025) demonstrated that land use changes significantly impacted soil carbon stocks. Agricultural land increased from 38.86% to 42.69%, and urban areas expanded from 0.37% to 3.11%, while shrubland and grassland areas declined. These changes led to a substantial reduction in total carbon stock, decreasing from 32.1 million tons in 2015 to 15.3 million tons in

2023, primarily due to deforestation and the conversion of land to agriculture. Srinivas *et al.* (2026) studied soil CS across seven cropping systems and two soil depths. They found that the deeper soil layer (20 to 40 cm) and certain cropping systems exhibited higher CS compared to the soil surface and fallow land. The importance of soil organic carbon and nitrogen sequestration in agricultural soils as a strategy to mitigate climate change has been recognized worldwide in the context of soil management. Global warming and the need to reduce atmospheric carbon dioxide have drawn researchers' attention to soil as a carbon reservoir and one of the most cost-effective solutions to decrease this greenhouse gas. Consequently, extensive research on carbon sequestration in soils is conducted annually around the world. Given that the Gyan region in Hamedan province features a combination of natural forest cover and agricultural land use—and that recent land use changes have occurred due to increased water availability, resulting in the conversion of much forest land to agriculture—this study focused on comparing the amounts of organic carbon and sequestered soil carbon across three land uses: forest, orchards, and agriculture, at two soil depths: 0–15 cm and 15–30 cm from the surface.

2. Materials and methods

2.1. Study area

The study area is located in the Gyan Plain, south of Nahavand city, Hamadan Province. The geographical location of the region on the map of Iran is between latitude $34^{\circ}11'05''$ and $34^{\circ}12'00''$ North, and longitude $48^{\circ}14'48''$ to $48^{\circ}19'48''$ East. The region is situated at an altitude of 1,563 meters above sea level. The average annual precipitation is 354 millimeters. Geomorphologically, the region consists of a piedmont plain and an alluvial fan. The area exhibits a xeric soil moisture regime and a mesic thermal regime (Banaei, 1998). According to the soil taxonomic key (2024), the soils in the forested areas are classified within the large groups Calcixerepts and Xerorthents, while the soils in the agricultural and woodland areas belong to the large group Calcixerepts. In general, wheat, barley, maize, canola, and sugar beet occupy a large portion of the agricultural land. Other important crops in the region include alfalfa, coriander, and sunflower, which are primarily cultivated under irrigated conditions. Figure 1 shows the location of the Gyan Plain in Hamedan Province, along with the sampling points.

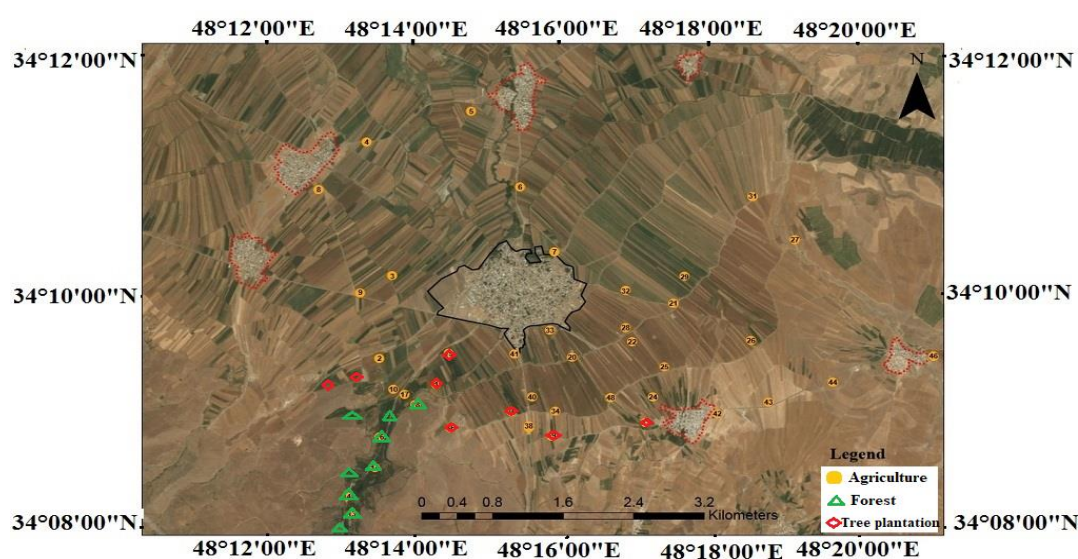


Figure 1. Satellite image of studied area and the sites of soil sampling.

2.2. Field and Laboratory Studies

A total of 48 soil sampling points were randomly selected, comprising 9 points from forest areas, 8 points from orchards and tree plantations, and 31 points from cultivated agricultural. At each point, soil samples were collected from two depths: 0–15 cm and 15–30 cm, along with clods from both depths. The selected points represent three land uses: forest (dominant species include Plantain, *Fraxinus syriaca*, and *Quercus*), agricultural lands (Sugar beet, Canola, Mazie, Wheat, Sunflower) and marshes located in this plain. All crops in the area have a history of more than 20 years. The marshland use includes some scattered orchards (such as walnut, apple, peach, apricot, etc.) and trees in wetlands. Due to its distance from forests and agricultural lands, this area was classified as a land use type called tree plantation. Bulk density was measured using the paraffin method (Black and Hartje, 1986). Particle size distribution was determined by the hydrometer method (Gee and Bauder, 1986), cation exchange capacity (CEC) was measured according to Sumner and Miller (1996). SOC was assessed following the method of Nelson and Sommers (1996). Calcium carbonate equivalent (CCE) was quantified using procedures outlined by Loppert and Suarez (1996). Moisture content was determined from the saturated paste by drying samples at 110 °C for 24 hours, as described by Gardner (1986). Soil acidity (pH) was measured in a 1:5 suspension of soil and distilled water (McLean and Watson, 1985), electrical conductivity (EC) was determined in a 1:5 extract of soil and distilled water (Rhodes, 1996), total nitrogen was measured by the Kjeldahl method (Bremner and Mulvaney, 1982), and organic carbon was analyzed using the modified Walkley-Black method (Nelson and Sommers, 1996) in the laboratory.

2.3. Statistical Descriptions

The data obtained from the experiments were analyzed using SPSS version 20.0 software. The design is completely random. After determining significant differences between treatments, the means were compared using Duncan's multiple range and Student's t-test, depending on the data. Pearson correlation coefficients were also calculated. Additionally, the necessary graphs were created using Excel 2019. Equation 1 (Zhao *et al.*, 2015) was used to estimate the amount of carbon stored per unit area:

$$SCS = 10000 \times \%OC \times BD \times E \quad (1)$$

SCS: Soil carbon sequestration rate in gm^{-2}

%OC: Carbon density at a given soil depth, expressed as a percentage.

BD: Soil specific gravity in gcm^{-3}

E: Soil depth (thickness in cm)

3. Results

3.1. Physicochemical properties

According to the results obtained at the surface depth (Table 1), SOC was calculated ranged from 1.7% in agricultural land to 4.4% in forest land. The highest CS of $123.62 \text{ tons ha}^{-1}$ was observed in agricultural land used for sugar beet cultivation, while the lowest, $118.44 \text{ tons ha}^{-1}$, was found in tree plantation land. Most soil samples exhibited a fine-textured, clayey texture. At the surface depth, the lowest average clay content (30.6%) was associated with forest land use, whereas the highest (40%) was observed in agricultural land. The average sand content in forest land use (43.9%) was the highest, while agricultural land use had the lowest average sand content (30.8%). The primary factor influencing soil texture in this region is the type of physiographic unit. Forests are predominantly found in hilly, mountainous, and alluvial fan areas, whereas agricultural lands are situated on piedmont plains. The results show that pH ranges from a minimum of 6.87 in the

tree plantation to a maximum of 7.8 in agricultural land used for sugar beet cultivation. On average, the lowest soil acidity was observed in tree plantation land use (Table 1). The CEC varied from 24.8 $\text{cmol} \cdot \text{kg}^{-1}$ in agricultural land used for wheat cultivation to 52.8 $\text{cmol} \cdot \text{kg}^{-1}$ in forest land. The high CS in forest land use can be attributed to its elevated CEC. Electrical conductivity was low across all land uses. The lime content of the soil ranged from 15% in forest land to 25.5% in tree plantation land. The bulk density ranged from 1.2 gcm^{-3} in agricultural land to 2.1 gcm^{-3} in tree plantation. However, the lowest average bulk density was observed in forest land use (1.6 gcm^{-3}), which may be attributed to the higher organic matter content and greater porosity in forest soils (Matinfar and Ghodsifard, 2014). The saturated moisture content varied from 39.75% in agricultural land to 88.93% in forest land. On average, the forest land exhibited the highest saturated moisture percentage, likely due to its elevated organic carbon content (Table 1). The results for the subsurface depth (Table 1) showed that the percentage of SOC at this depth ranged from 1.28% in agricultural land to 4.1% in tree plantation. The highest CS of 132.44 tons ha^{-1} was recorded in agricultural land, while the lowest CS of 29.8 tons ha^{-1} was found in tree plantation. The soil texture was fine and clayey, similar to that of the surface layer. According to Table 1, the highest average clay content was observed in agricultural land (41.77%), and the lowest in forest land (36.22%). The higher average bulk density observed in agricultural land compared to the lower value in forest land can be attributed to differences in organic matter content (Table 1). Results from all subsurface sampling points indicated that soil pH ranged from 7.02 in the tree plantation to 7.8 in certain locations of agriculture land. The soil's CEC varied from 22 $\text{cmol} \cdot \text{kg}^{-1}$ in the tree plantation to 50.4 $\text{cmol} \cdot \text{kg}^{-1}$ in the forest land use. Electrical conductivity decreased slightly in all three land uses compared to the topsoil (Table 1); however, differences between land uses were minimal, and the soils were found to be non-saline. Additionally, according to Table 1, tree plantation exhibited the highest average lime content (34.6%), while forest land had the lowest average lime content (22.7%). At subsurface depths, forest land showed the highest average moisture content, whereas agricultural land had the lowest average saturated moisture percentage (Table 1).

Table 1. The mean selected physico-chemical characteristics of soils studied in surface and subsurface depth in different land uses.

Characteristics		Texture %			C/N	Total N (%)	SCS (Tha^{-1})	O.C (%)	BD (gcm^{-3})	CCE (%)	CEC ($\text{cmol} \cdot \text{kg}^{-1}$)	EC (dSm^{-1})	pH
Land use	Depth (cm)	Sand	Silt	Clay									
Forest	0-15	43.9	25.5	30.6	7.00	0.56	85.3	3.90	1.63	23.7	37.2	0.24	7.5
Agriculture		30.8	29.2	40	6.45	0.45	62.8	2.90	1.68	31.5	31.7	0.23	7.4
Tree plantation		37.4	27.8	34.8	5.40	0.71	84.4	3.80	1.70	34.2	34.8	0.33	7.14
Forest	15-30	37.1	26.7	36.2	-	-	77.6	3.25	1.70	22.7	39.6	0.14	7.61
Agriculture		30.0	28.2	41.8	-	-	81.8	2.60	1.80	30.2	33.2	0.15	7.48
Tree plantation		34.3	26.6	39.1	-	-	56.0	3.24	1.80	34.6	31.4	0.18	7.29

SCS: Soil Carbon Sequestration; OC: Organic Carbon; BD: Bulk density; CEC: Cation exchange capacity; CCE: Calcium carbonate equivalent; EC: Electrical Conductivity.

Pearson correlation between all parameters was calculated separately for two soil depths, 0–15 cm and 15–30 cm. The results are presented in Tables 2 and 3. The results showed that SOC has a positive and significant correlation with the percentage of saturated moisture at the surface depth ($r = 0.55$, $p < 0.01$) and at the subsurface depth ($r = 0.33$, $p < 0.05$). There is a significant positive correlation between the amount of sequestered carbon and saturated moisture content at the surface ($r = 0.43$, $p < 0.01$) and subsurface ($r = 0.20$, $p < 0.05$) depths. The correlation results show a significant negative correlation between SOC and the combined silt and clay fraction (fine soil components) at both surface ($r = -0.33$, $p < 0.05$) and subsurface depths ($r = -0.45$, $p < 0.01$). A significant negative relationship was observed between CS content and the silt and clay components of the soil at both surface ($r = -0.31$, $p < 0.05$) and subsurface ($r = -0.27$, $p < 0.05$) depths. Additionally, a significant positive relationship was found between the amount of SOC and sand content at the surface ($r = 0.32$, $p < 0.05$) and subsurface ($r = 0.46$, $p < 0.05$) depths. However, the positive relationship between CS and sand content was not significant. At surface depth, SOC exhibits a significant positive correlation with nitrogen ($r = 0.38$, $p < 0.01$). CS at this depth also showed a positive relationship with total soil nitrogen content; however, this relationship was not statistically significant. The correlations between SOC and CEC at the surface depth ($r = 0.33$, $p < 0.05$) are positive and significant. At the surface depth, CS also shows significant positive correlations with CEC ($r = 0.46$, $p < 0.01$).

However, for both SOC and CS, CEC showed a positive but not statistically significant relationship with subsurface depth. There was a negative relationship between soil density and organic carbon content at both surface and subsurface depths, although this relationship was not statistically significant. In contrast, soil bulk density exhibited a significant positive correlation with CS at both surface ($r = 0.59$, $p < 0.01$) and subsurface ($r = 0.63$, $p < 0.01$) depths. The analysis also revealed that soil lime content had a negative relationship with SOC content at the surface depth and subsurface depth ($r = -0.35$, $p < 0.01$). Similarly, CS showed a negative relationship at the surface depth and a significant negative correlation at the subsurface depth ($r = -0.36$, $p < 0.01$).

Table 2. Correlation coefficient between soil properties in 0-15 cm depth.

Parameters	pH	EC	CEC	CCE	BD	Clay	Silt	Sand	Moist	Total N	O.C	C/N	Clay+ Silt	C.S
pH	1													
EC	-0.17	1												
CEC	0.14	0.21	1											
CCE	-0.17	0.10	-0.25	1										
B. D	0.22	-0.07	*0.32	-0.21	1									
Clay	-0.08	-0.13	0.01	**0.37	0.18	1								
Silt	-0.15	0.04	0.03	-0.04	-0.07	0.24	1							
Sand	-0.14	0.05	-0.03	-0.24	-0.07	** 0.79	** 0.78	1						
Moist	0.216	**0.43	**0.48	-0.25	-0.18	-0.24	-0.15	0.17	1					
Total N	-0.21	**0.43	0.16	0.22	-0.13	-0.25	0.07	0.11	*0.285	1				
O.C	0.13	*0.34	*0.33	-0.12	-0.12	** 0.39	-0.12	*0.32	**0.55	**0.38	1			
C/N	0.15	-0.115	-0.01	-0.25	-0.03	0.17	-0.14	-0.01	0.03	** 0.72	0.16	1		
Clay+Silt	-0.15	-0.06	0.02	0.23	-0.14	**0.79	**0.79	** 0.99	-0.18	-0.112	*-0.33	0.17	1	

C.S	0.21	0.24	**0.46	-0.21	**0.59	-0.21	-0.127	0.21	**0.43	0.25	**0.82	0.09	-0.31*	1
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*, **are significant at 1 and 5 (%) probability level, respectively.

Table 3. Correlation coefficient between soil properties in 15-30 cm depth.

Parameters	pH	EC	CEC	CCE	BD	Clay	Silt	Sand	Moist	O.C	Clay+ Silt	C.S
pH	1											
EC	-0.07	1										
CEC	**0.44	0.19	1									
CCE	-0.05	0.01	**	1								
BD	-0.04	0.09	-0.04	-0.16	1							
Clay	0.05	-0.01	0.24	**0.43	0.15	1						
Silt	-0.22	0.18	0.18	0.16	0.04	*0.31	1					
Sand	0.19	-0.11	-0.21	**	-0.12	**	**	1				
Moist	0.23	**0.57	**0.57	-0.03	-0.11	0.26	0.06	-0.21	1			
O.C	0.11	0.17	0.19	*	-0.02	**	*	**0.46	*0.33	1		
Clay+Silt	0.01	0.19	0.18	*0.37	0.116	**0.79	**0.71	**	0.15	**	1	
C.S	0.04	0.17	0.17	-	**0.63	-0.24	-0.19	0.26	0.22*	**0.75	-	1

**, * are significant at 1 and 5 (%) probability level, respectively.

3.2. Effect of depth on SOC and CS

The results of comparing the means using Student's t-test for SOC at depths of 0–15 cm and 15–30 cm is presented in Table 4. As shown, there is a significant difference between the two depths.

Table 4. T-Student analysis for SOC between to depth.

	df	t	sig
Surface and sub surface depth	47	5.263	**0.00

** are Significant at 99 (%) probability level.

It can be concluded that depth significantly affects SOC ($p < 0.01$), with unequal means between depths. Organic carbon content at the surface depth is higher than at the subsurface depth, as indicated by the positive t-statistic, shown in Figure 2. The average CS was also compared between the two depths using Student's t-test. No significant difference in CS was found between surface and subsurface soil depths, as illustrated in Figure 2.

3.3. The effect of different land uses on SOC at two depths

An analysis of the impact of land use on SOC at the surface depth revealed significant differences among treatments. Variance analysis results (Table 5) and Duncan's multiple range test (Table 6) for organic carbon in forest, tree plantation, and agricultural land uses demonstrated that different land uses influence SOC levels differently. The highest average SOC was observed in forest land use, while the lowest was found in agricultural land use. Figure 4 illustrates the comparison of average organic carbon across land uses, highlighting a

significant difference between agricultural land and both tree plantations and forests.

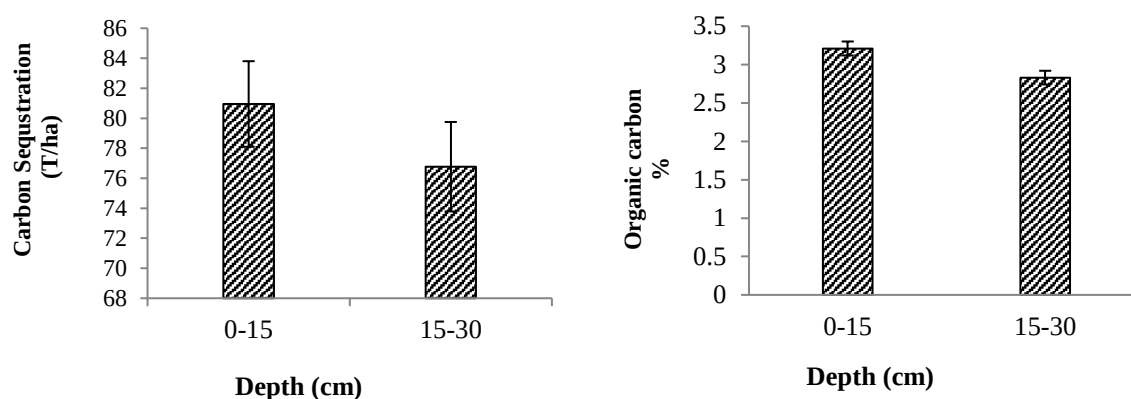


Figure 2. Mean comparison of SOC and CS in two surface and subsurface depths.

Table 5. Analysis variance of land use effect on SOC in surface and subsurface depths.

Depth (cm)		Sum of Squares	df	Mean Square	F	sig
0-15	Between Groups	9.497	2	4.749	23.53	0.00**
	Within Groups	9.079	45	0.202	-	-
	Total	18.576	47	-	-	-
15-30	Between Groups	4.483	2	2.24	7.467	0.002**
	Within Groups	13.509	45	0.30	-	-
	Total	17.99	47	-	-	-

Table 6. Means comparison of SOC effect in different land uses in two depths.

Depth (cm)	Land use type	Mean
0-15	Forest	3.84 ^a
	Tree plantation	3.77 ^a
	Agriculture	2.88 ^b
15-30	Forest	3.25 ^a
	Tree plantation	3.24 ^a
	Agriculture	2.61 ^b

Means followed by different letters are significantly different at $p < 0.05$ by Duncan's test.

The highest and lowest average SOC levels are observed in forest and agricultural lands, respectively (Figure 3). The greater SOC in forests compared to agricultural areas at a depth of 30 cm is attributed to the reduced input of plant residues into the soil in cultivated lands.

The average SOC content in forest and tree plantation areas is not statistically significantly different. It can be inferred that the trees in nearby marsh areas are also largely undisturbed and free from tillage operations, which influences the organic carbon levels in woodlands. This study concludes that soil depth has a significant effect on SOC content at all sampling points.

However, there was no significant difference in SOC between different land uses when comparing surface and subsurface depths. At both depths, only agricultural land use showed a significant difference in SOC compared to forest and tree plantation.

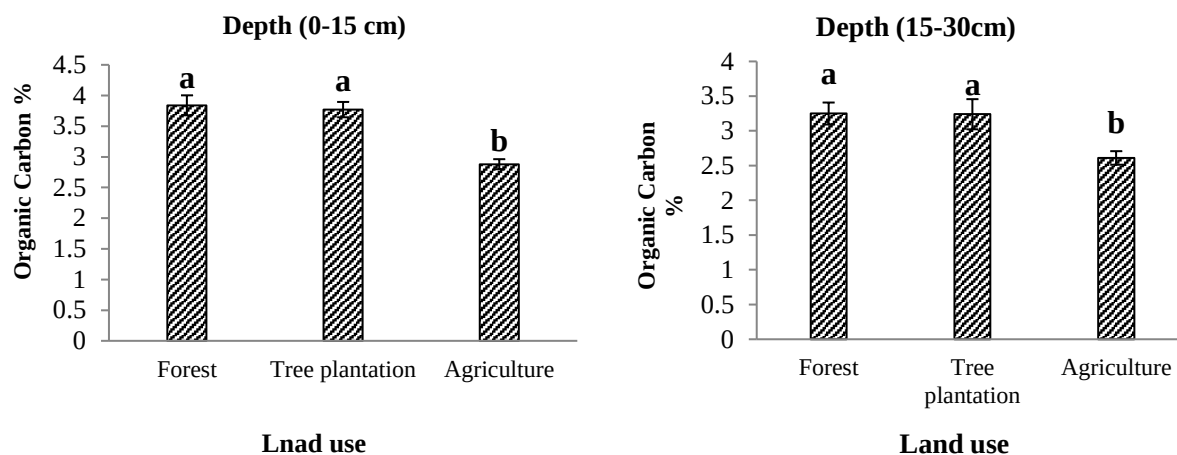


Figure 3. Mean comparison of three land uses organic carbon in two surface and subsurface depths.

3.4. The effect of land use on CS at surface and subsurface depths

At surface depths, the variance analysis table (Table 7) indicates a significant difference between land uses. Mean comparisons were conducted using Duncan's multiple range test, with the results presented in Table 8.

Table 7. Analysis variance of land use effect on CS in surface depth.

	Sum of Squares	Df	Mean Square	F	Sig
Between Groups	5844.52	2	2922.260	10.493	0.00**
Within Groups	12532.023	45	278.489		
Total	18376.544	47			

Table 8. Mean comparison of CS effect in different land uses in surface depth.

Land use type	Mean
Tree plantation	96.96 ^a
Forest	94.85 ^a
Agriculture	72.79 ^b

Means followed by different letters are significantly different at $p < 0.01$ by Duncan's test.

The results indicate that different land uses have varying effects on CS. The highest average sequestration is associated with tree plantation land use, while the lowest average sequestration occurs in agricultural land use. There is no statistically significant difference in CS between tree plantation and forest land uses. Additionally, the effect of treatment was not significant at subsurface depths. Conversion of forest areas to agricultural land has resulted in a decrease in CS, whereas no such decrease in carbon storage was observed in tree plantation areas.

3.5. The effect of different cultivation on SOC and CS in agricultural lands

In examining the effect of treatment, no statistically significant difference was found in the percentage of SOC among the treatments (types of crop cover) at both surface and subsurface depths. At both depths, maize exhibited a slightly higher percentage of organic carbon than the other covers, with canola, sugar beet, wheat, and sunflower ranked sequentially after maize. A comparison of Duncan's mean values for CS at surface depth in maize, canola, sugar beet, sunflower, and wheat crops in the agricultural lands of the studied region showed that maize and canola had the highest CS, while wheat had the lowest (Table 9 and Figure 4). Similar results were observed at subsurface depth, although the differences were not statistically significant.

Table 9. Analysis variance of cultivation type effect on CS in surface depth.

	Sum of Squares	Df	Mean Square	F	Sig
Between Groups	1337.96	5	334.49	1.6595	0.003*
Within Groups	5242.77	26	201.649		
Total	6580.73	30			

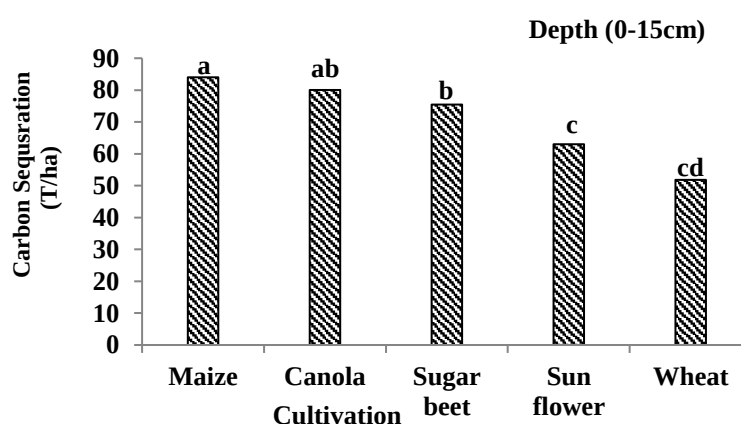


Figure 4. Mean comparison of CS in different cultivations in surface depth.

In examining the effect of land use type and crop type on the C/N ratio, no significant differences were found between the treatments. However, the C/N ratio was higher in forest land compared to agricultural land, followed by tree plantations. Among the crops, canola cultivation exhibited the highest average C/N ratio, followed closely by sugar beet. Sunflower, maize, and wheat showed only minor variations in their C/N ratios.

4. Discussion

The relationships between SOC, CS, and soil physical and chemical properties provide important insights into the factors controlling carbon dynamics in calcareous soils. In the present study, SOC showed significant relationships with several soil properties, indicating that soil characteristics play an important role in regulating carbon accumulation and stabilization. Among these properties, soil texture had a significant influence on SOC. A significant positive correlation was observed between SOC and sand content at both surface and subsurface depths. This finding suggests that, under the conditions of the studied calcareous soils, coarse-textured

soils may support greater SOC accumulation, possibly due to improved soil aeration, root development, and vegetation productivity. Similar effects of soil texture on SOC distribution have been reported by Abdi *et al.* (2011), who emphasized the role of soil texture in controlling organic carbon storage. However, although clay minerals are generally considered important stabilizing agents for organic carbon through physical protection and reduced decomposition rates (Six and Pustian, 2014; Wang *et al.*, 2016), our results showed a negative relationship between SOC and clay plus silt content. This difference may be related to the specific characteristics of calcareous soils in the study area, where carbonate content, climatic conditions, and limited organic matter inputs may influence carbon stabilization mechanisms. Therefore, the effect of soil texture on SOC storage is not solely determined by clay content but also depends on the interaction between mineral composition, environmental conditions, and land management practices.

The positive relationship observed between SOC and total nitrogen at the surface depth indicates the close coupling between carbon and nitrogen dynamics in the studied soils. In the present study, higher SOC was associated with greater nitrogen content, which can be attributed to the contribution of organic matter to both carbon and nitrogen pools. Similar relationships between soil carbon and nitrogen have been reported in previous studies, particularly in surface soil layers where biological activity and organic matter inputs are generally higher (Awoonor *et al.*, 2022). The stronger association in surface soils compared with deeper layers may be related to the greater accumulation of plant residues and root-derived organic inputs near the soil surface. In addition, increased nitrogen availability can enhance plant productivity and residue production, which may subsequently contribute to long-term carbon storage (Ratnayake *et al.*, 2017). The positive correlation between SOC and CEC at the surface depth confirms the important role of organic matter in improving soil chemical properties. Soil organic matter contributes substantially to CEC because functional groups associated with organic compounds provide additional exchange sites for nutrient retention (Hansen *et al.*, 2016). Therefore, the observed relationship between SOC and CEC suggests that soils with greater organic carbon content may have a higher capacity for nutrient retention and improved soil fertility. Similarly, the positive relationship between CS and CEC indicates that organic carbon accumulation contributes not only to carbon storage but also to broader improvements in soil quality. In this study, SOC and CS were higher in surface soils than in subsurface soils. This pattern is expected because surface layers receive greater inputs of plant residues, litter deposition, and root biomass, which are the primary sources of soil organic matter. The gradual decomposition of these materials and their conversion into humus mainly occur near the soil surface, leading to greater carbon accumulation and improved soil properties in this layer (Zhou *et al.*, 2015; Akpa *et al.*, 2016). Similar depth-related patterns have been reported by Olson and Al-Kaisi (2015) and Akpa *et al.* (2016), who found that a large proportion of soil carbon is concentrated in the upper soil layers due to higher organic inputs and biological activity. Bulk density showed a significant negative relationship with CS at both soil depths, indicating that soil compaction negatively affects carbon storage. Higher bulk density is commonly associated with reduced soil porosity, restricted root growth, lower microbial activity, and decreased incorporation of organic residues into soil aggregates. In the present study, this relationship may be related to intensive cultivation practices in agricultural lands, where repeated tillage can disrupt soil aggregates and increase compaction, resulting in SOC losses. Similar effects of soil disturbance and compaction on carbon dynamics have been reported by Awoonor *et al.* (2022) and Zhao *et al.* (2022). The negative relationship between lime content and SOC and CS suggests that carbonate-rich conditions may influence carbon accumulation processes in the studied

calcareous soils. Although some studies have reported higher SOC concentrations in calcareous soils due to carbonate-associated stabilization mechanisms (Calvo de Anta *et al.*, 2020), the effect of lime content can vary depending on climate, vegetation cover, organic matter inputs, and soil management practices. Therefore, the observed relationship in this study may reflect the combined effects of calcareous soil characteristics and differences in land use rather than a direct inhibitory effect of lime on carbon storage.

Soil depth significantly affected SOC content in the present study, whereas its effect on CS was not significant. The higher SOC concentration observed in the surface layer (0–15 cm) compared with the subsurface layer (15–30 cm) can be attributed to the greater accumulation of organic inputs at the soil surface, including litter deposition, crop residues, and root-derived carbon. These organic materials are gradually decomposed and incorporated into the soil, resulting in greater carbon accumulation in the upper soil layer. Similar depth-related patterns have been reported by Zhao *et al.* (2015), Olson and Al-Kaisi (2015), and Akpa *et al.* (2016), who found that soil carbon is generally concentrated in the upper layers due to higher biological activity and continuous organic matter inputs. The lack of a significant difference in CS between the two depths, despite differences in SOC concentration, may be related to the combined effect of SOC content and soil bulk density in carbon stock calculations. Carbon stock is determined not only by SOC concentration but also by soil mass, which is influenced by bulk density and sampling depth. Therefore, differences in SOC concentration between layers may not necessarily result in significant differences in total carbon stocks. Similar findings have indicated that carbon distribution with depth depends on the interaction between organic matter inputs, soil physical properties, and calculation methods. The decrease in SOC with increasing depth is particularly important in managed agricultural soils, where organic matter inputs are mainly concentrated near the surface. The upper soil layer is more directly affected by vegetation cover, residue management, and tillage practices. Therefore, maintaining surface organic matter through residue retention, reduced tillage, and improved vegetation management can play an important role in enhancing SOC storage in agricultural soils.

The results of this study demonstrated that land-use type significantly influenced SOC and CS, highlighting the important role of vegetation cover and management practices in regulating soil carbon dynamics. In the present study, forest and tree plantation areas showed higher SOC and CS values compared with agricultural lands, while no significant differences were observed between forest and tree plantation systems. This finding indicates that perennial vegetation systems can maintain soil carbon storage at levels comparable to natural forests under the conditions of the study area. The higher SOC content observed in forest soils compared with agricultural soils can be explained by several mechanisms, including continuous litter input, greater root biomass, reduced soil disturbance, and improved microclimatic conditions under dense vegetation cover. Forest canopies reduce soil temperature fluctuations and contribute to slower organic matter decomposition, thereby promoting carbon accumulation in soil (Wang *et al.*, 2014; Zhao *et al.*, 2015). In contrast, agricultural soils generally experience greater disturbance due to tillage operations, residue removal, and reduced vegetation cover, which accelerate organic matter decomposition and decrease carbon inputs to the soil (Sperow, 2016; Wang *et al.*, 2016; Prakash and Shimrah, 2023; Tikuye *et al.*, 2025). Our results are consistent with previous studies showing that conversion of natural ecosystems to cultivated land leads to substantial SOC and CS losses. For example, Hammad *et al.* (2020) reported greater CS potential in forest ecosystems compared with croplands, while Deng *et al.* (2016) indicated that conversion of forests or perennial grasslands to agricultural systems can reduce SOC by 20–43%. The similarity between these findings and our results confirms the negative impact of

intensive agricultural practices on soil carbon storage (Tikuye *et al.*, 2025). However, the magnitude of carbon loss after land-use conversion may vary depending on climate conditions, soil type, land-use history, and management intensity. An important finding of this study was that tree plantations showed carbon storage levels comparable to natural forests. The absence of a significant difference between these two land uses suggests that established perennial vegetation systems may compensate for some of the carbon losses associated with land degradation. Dense vegetation cover, continuous organic matter inputs, reduced soil disturbance, and extensive root systems in tree plantations contribute to carbon accumulation and stabilization. Similar observations have been reported in orchard and agroforestry systems, where lower tillage intensity and greater vegetation cover resulted in improved SOC storage compared with annual croplands (Rasouli Sedqiani *et al.*, 2015; Wang *et al.*, 2016).

The higher CS observed in forest and tree plantation systems in the Gyan region may also be related to local environmental conditions. Greater precipitation in highland areas can enhance vegetation productivity and increase organic matter inputs to the soil, thereby promoting carbon accumulation (Chen *et al.*, 2022). Therefore, the interaction between land use and environmental conditions should be considered when evaluating soil carbon sequestration potential. The reduction of SOC and CS following forest conversion to agricultural land observed in this study has important implications for land management in calcareous soils. Maintaining perennial vegetation cover, reducing soil disturbance, and increasing organic matter return are essential strategies for conserving soil carbon. The similarity between tree plantations and forests suggests that well-managed tree-based systems may represent a practical approach for enhancing carbon storage in degraded agricultural landscapes while providing additional ecological benefits.

Crop type was also found to influence carbon sequestration potential within agricultural systems. In the present study, maize and canola showed higher CS values compared with wheat, suggesting that crop characteristics and biomass production play important roles in determining carbon inputs to agricultural soils. The greater CS observed under maize cultivation may be related to its high aboveground biomass production, extensive root system, and greater residue return to the soil after harvest. Previous studies have also highlighted the potential of maize-based systems for enhancing soil carbon storage due to their high biomass production and contribution of crop residues (Liu, 2014; Lal *et al.*, 2015; De Los Rios *et al.*, 2022). Canola also exhibited relatively high CS values, which may be associated with its considerable root development and the addition of organic residues to the soil. The input of both aboveground residues and belowground biomass contributes to increasing organic carbon availability and improving carbon storage capacity. These findings support the idea that crop selection can be an important management factor for improving CS in agricultural soils. In contrast, wheat cultivation showed the lowest CS values among the evaluated crops. This result may be attributed to lower biomass return, reduced residue incorporation, and differences in root biomass compared with maize and canola. Similar results have been reported by Zhao *et al.* (2015), who found that certain wheat-based cropping systems may reduce SOC accumulation when residue inputs are insufficient. However, other studies have demonstrated that wheat-based rotations combined with appropriate management practices, such as fertilizer application and crop diversification, can increase CS over time (Zhao *et al.*, 2022). These differences indicate that the effect of a crop type on carbon storage depends not only on the crop species itself but also on rotation systems, residue management, and soil management practices. Overall, the results of this study demonstrate that land-use type and crop selection are key factors controlling SOC and CS in calcareous soils. Conversion of forest land to intensive

agriculture reduces soil carbon storage, whereas perennial vegetation systems such as forests and tree plantations can maintain higher carbon stocks. Within agricultural systems, selecting crops with greater biomass production and implementing practices such as crop rotation, residue retention, and reduced tillage can help minimize SOC losses and enhance soil carbon sequestration.

5. Conclusion

The results of this study demonstrated that land-use type is a key factor controlling soil organic carbon (SOC) and carbon sequestration (CS) in calcareous soils. Forest and tree plantation systems maintained significantly higher SOC and CS levels compared with agricultural lands, while no significant differences were observed between forests and tree plantations. These findings indicate that perennial vegetation systems can preserve soil carbon stocks and may serve as effective strategies for reducing carbon losses caused by land-use change. Soil depth significantly influenced SOC distribution, with higher organic carbon concentrations observed in surface soils due to greater organic matter inputs from plant residues and litter accumulation. However, the effect of depth on CS was not significant, suggesting that carbon storage is influenced by the interaction between SOC concentration and soil physical properties.

Among agricultural systems, crop type affected carbon sequestration potential. Maize and canola showed greater CS capacity than wheat, likely due to higher biomass production and organic residue inputs. Therefore, selecting appropriate crops and implementing management practices such as crop rotation and residue retention can contribute to maintaining and enhancing soil carbon storage. Overall, the conversion of forest land to agricultural systems resulted in SOC and CS losses in the studied region, whereas conversion to tree plantations did not significantly reduce carbon storage. Future studies should consider both soil and vegetation carbon pools to provide a more comprehensive assessment of CS potential at the landscape scale.

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Authors' contribution

Conceptualization, S.S.H. and T.T.; methodology, S.S.H.; software, T.T.; validation, S.S.H. and T.T.; formal analysis, S.S.H. and T.T.; investigation, S.S.H. and T.T.; resources, S.S.H. and T.T.; data curation, S.S.H. and T.T.; writing—original draft preparation, S.S.H.; writing—review and editing, S.S.H.; visualization, S.S.H.; supervision, S.S.H.; project administration, S.S.H.; funding acquisition, S.S.H., T.T., and B. A; All authors have read and agreed to the published version of the manuscript.

Data availability

Data available on request from the authors.

Ethical considerations

The authors avoided from data fabrication and falsification.

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Conflict of interest

The authors declare no conflicts of interest.

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