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Geomorphological Analysis of Soil Organic Carbon Sequestration Potential in Landforms of Miandasht (Jajarm) and Chehel-Dokhtaran (Esfarayen) Regions, Iran

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ABSTRACT

Aims The increase in greenhouse gases, particularly carbon dioxide in the atmosphere, is a major environmental challenge for sustainable development, and carbon sequestration is a fundamental solution to mitigate it. The present study was conducted with the aim of determining the spatial distribution of soil organic carbon (SOC) sequestration and analyzing the controlling effect of geomorphological landforms on it in two regions: Miandasht of Jajarm (protected area) and Chehel-Dokhtaran of Esfarayen (free-management area).

Methodology This study was conducted using a causal-comparative field-laboratory method combined with generalized linear modeling (GzLM). To identify the landforms, Landsat 8 OLI satellite imagery (August 2022) was integrated with a 30-meter resolution SRTM Digital Elevation Model (DEM). Stratified random sampling was performed across a total of 38 points (at a depth of 0-30 cm), and the soil organic carbon content was determined in the laboratory using the Walkley-Black wet oxidation method. Due to the non-normal distribution and positive skewness of the soil organic carbon data, a GzLM with a gamma distribution and a logarithmic link function was utilized.

Findings The results showed that the mean soil organic carbon (SOC) content in Miandasht of Jajarm (0.268%) was higher than that in Chehel-Dokhtaran of southern Esfarayen (0.199%). Among the identified landforms in the study area, floodplains exhibited the highest sequestration capacity due to their textural characteristics and sediment stability. The GzLM analysis (significance level <0.001) confirmed that the geomorphological structure was the primary factor driving variations in SOC, whereas neither the independent macro-level management status nor the interaction effect between management and landforms was statistically significant.

Conclusion Soil organic carbon distribution in the region is completely governed by the inherent characteristics of landforms. Erosion processes, particularly in badlands due to the lithological sensitivity of marly formations and continuous topsoil washing, override the natural carbon sequestration capacities. Conversely, lowlands exhibit a higher potential for carbon stability due to the formation of organo-mineral complexes. The non-significance of the interaction effect in the statistical model proves that geomorphic factors are the ultimate controllers of carbon distribution.

Keywords Carbon Sequestration; Generalized Linear Modeling; Geomorphological Landforms; Land Management; Ecological Sustainability

CITATION LINKS

[Alderson *et al.*, 2019] Geomorphological ...; [Amirahmadi & Zanganeh Asadi, 2017] Generalization ...; [Babaei *et al.*, 2016] Modeling of soil organic ...; [Buraka *et al.*, 2022] Soil organic carbon and its' stock potential in ...; [Fal Soleiman & Chakoshi, 2011] Socio-economic monitoring of the international ...; [Falahatkar *et al.*, 2014] The impact of primary terrain attributes and land ...; [Farokhzadeh *et al.*, 2023] Effective physiological ...; [Geremew *et al.*, 2023] Impact of land use/cover change ...; [Ghimire *et al.*, 2024] Carbon sequestration through ...; [Hancock *et al.*, 2010] Hillslope and catchment scale soil organic carbon ...; [Heidari *et al.*, 2010] Carbon ...; [Hirmas *et al.*, 2010] Spatial ...; [Jafarian & Ghorbani , 2024] Prediction of soil carbon sequestration in rangelands regarding the depth and elevation of ...; [Janjani *et al.*, 2022] Effects ...; [Jobbágy & Jackson, 2000] The vertical ...; [Kamali & Sadeghipour, 2018] Investigation of the ...; [Lal *et al.*, 2015] Carbon ...; [Lasanta *et al.*, 2021] A review ...; [Lin *et al.*, 2026] Global ...; [Long *et al.*, 2021] Relationship between the slope microtopography ...; [Mahdavi *et al.*, 2018] The effect of land-use ...; [Maleki *et al.*, 2019] Role of geomorphic surface on the above-ground biomass ...; [Miri *et al.*, 2025] Analysis the impacts of ...; [Mo *et al.*, 2024] Effects of aeolian deposition on soil ...; [Nelder & Wedderburn, 1972] Generalized ...; [Ng & Cribbie, 2019] The gamma generalized linear model, log transformation, and the ...; [Noormohammadi & Esmailzadeh, 2015] Variability of ...; [Pahlavan-Rad & Akbari-Moghaddam , 2017] Controlling ...; [Palmtag *et al.*, 2018] Landform ...; [Plaza *et al.*, 2018] Soil ...; [Sanderman *et al.*, 2017] Soil ...; [Scott & Wohl, 2018] Geomorphic regulation of floodplain soil ...; [Shi *et al.*, 2019] Soil ...; [Stover *et al.*, 2025] Multi-scale influences on the fertile island effect ...; [Wang *et al.*, 2025] Iron-driven organic carbon sequestration in arid saline-alkali ...; [Wiesmeier *et al.*, 2019] Soil organic carbon storage as a ...; [Xiao, 2015] Soil ...; [Yimer *et al.*, 2006] Soil property variations in relation to ...; [Yue *et al.*, 2026] Soil carbon ...; [Zarrinkafsh *et al.*, 2016] The carbon sequestration in ...;

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Introduction

The unprecedented increase in the concentration of carbon dioxide, as one of the main drivers of climate change, has revealed the need to apply effective solutions for curbing greenhouse gases. In this context, soil organic carbon sequestration is regarded as a strategic and sustainable approach to capturing atmospheric carbon. Soil organic carbon is the biologically derived part of soil carbon and constitutes about 58% of total soil organic matter [Lal *et al.*, 2015]. As the largest carbon reservoir in terrestrial ecosystems, soils, with a storage capacity of 1500 to 1800 petagrams in the top meter and containing three to four times more organic carbon than vegetation and two to three times more than the atmosphere, play an irreplaceable role in the global carbon cycle [Jobbágy & Jackson, 2000; Sanderman *et al.*, 2017; Wiesmeier *et al.*, 2019]. Therefore, the proper management and protection of these huge carbon reservoirs is of particular importance as a key solution in formulating strategies for mitigating the effects of climate change.

Arid and semi-arid regions, covering more than one third of the Earth's land surface, host a considerable share (almost one third) of the world's soil carbon reserves. In these climatic zones, the interaction among water, land use, and management practices plays a decisive role in carbon uptake and storage [Ghimire *et al.*, 2024; Plaza *et al.*, 2018]. Because of the moisture deficit in these regions, the carbon sequestration potential can be strongly affected by environmental and geomorphological factors. Factors such as slope, aspect, elevation, and landform type, by influencing erosion and sedimentation processes, soil moisture, and the distribution of vegetation, play a decisive role in the sequestration potential of soil organic carbon [Yimer *et al.*, 2006; Maleki *et al.*, 2019]. In this regard, the influence of landform characteristics on the spatial and temporal distribution of soil organic carbon is of great importance for land management and carbon sequestration [Hancock *et al.*, 2010]. In this research, a landform refers to any distinct unit of the land surface with a particular shape, origin, and dominant processes (such as a floodplain or badland hills), and management status refers to the type and intensity of protection and use of the land (exclosure versus free grazing).

Although many international and national studies have examined the relationship between geomorphological characteristics and the sequestration potential of soil organic carbon and have explained the importance of topography and of processes related to erosion and sedimentation, the pivotal role of landforms and geomorphological units in this regard has received less attention; a detailed examination of the effect of these units and geomorphological features on carbon storage capacity, especially under different management approaches in the desert ecosystems of Iran, has been less evaluated and requires deeper investigation. At the global level, numerous studies have examined the role of geomorphological factors at different scales, from individual slopes to watersheds. For example, these studies show a strong relationship between the concentration of soil organic carbon and slope position and a wetness index derived from a high-resolution digital elevation model, and they emphasize the relative stability of soil carbon in the absence of human disturbance and the role of plant biomass (itself controlled by topography) as the main source of carbon [Hancock *et al.*, 2010]. Research findings confirm that factors such as elevation, slope, and landform type (such as terraces and hillslopes) significantly affect the soil organic carbon content and that areas with gentler slopes and terraces have a higher potential for organic carbon accumulation because of sedimentation and more favorable moisture conditions [Yimer *et al.*, 2006].

The assessment of different topographic positions on soil organic carbon stocks confirms that soil organic carbon values are strongly correlated with landform changes. Accordingly, the position on the slope and elevation, by controlling the rates of erosion and sedimentation, creates spatial heterogeneity in soil carbon, which is very important for sustainable land management and carbon sequestration programs [Long *et al.*, 2021]. In addition, examining the effect of erosion and sedimentation on the distribution of soil carbon shows that erosion-prone areas face carbon loss, whereas depositional lands (such as footslopes and valley floors) show higher densities of organic carbon [Geremew *et al.*, 2023].

In Iran, although studies focusing on the direct relationship between specific geomorphological landforms and soil organic carbon sequestration are not as extensive as foreign studies, research has been carried out on the assessment of soil carbon and the factors affecting it in various Iranian ecosystems. In this regard, in an examination of the effect of topographic factors (slope, aspect, and elevation) on soil organic carbon storage in the semi-arid rangelands of the Gonbad basin, the results showed that these factors control the spatial distribution of organic carbon through changes in vegetation density and erosion rate; north-facing slopes have higher carbon storage because of more favorable moisture conditions and denser vegetation, whereas south-facing slopes have the least carbon because of soil erosion, thin soils, and poor vegetation [Farokhzadeh *et al.*, 2023]. In addition, an assessment of the effect of land-use change from rangeland to agriculture on soil carbon sequestration in Ilam County indicates that land-use change has a strong effect on the amount of carbon sequestration [Mahdavi *et al.*, 2018]. In a relatively flat plain, an examination of the role of the physical and chemical properties of soil and microtopography in the spatial distribution of soil organic carbon also showed that, even in apparently level plains, slight changes in elevation and small irregularities can affect the patterns of accumulation and dispersion of soil organic carbon [Pahlavan-Rad &

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Akbari-Moghaddam, 2017]. The carbon sequestration project in the Rudab district of Sabzevar [Amirahmadi & Zanganeh Asadi, 2017] showed that comprehensive and coordinated management based on the all-round participation of people plays a key role in reducing the damage caused by desertification and preventing the degradation of soil and water resources. In addition, the evaluation of the international carbon sequestration project in the Hosseinabad-e Ghinab plain of Sarbisheh showed that livestock overgrazing was the main cause of soil degradation in the sensitive lands of the region [Fal Soleiman & Chakoshi, 2011]. Despite this background, the effect of landforms on soil organic carbon storage under different management approaches in the deserts of Iran has been little studied. Accordingly, the present research was carried out with the aim of analyzing the role of landforms and geomorphological units in soil organic carbon storage and comparing the effect of two management approaches on it in the Miandasht protected area of Jajarm and the freely managed Chehel-Dokhtaran area south of Esfarayen.

Methodology

Research method and statistical population

In terms of purpose, the present research was applied, and in terms of method it was a field–laboratory study with a causal-comparative design; that is, soil organic carbon was measured and compared in two areas with different management status (protected and free) and in seven landforms common to both (a 7×2 factorial design). The statistical population was the surface soil (0–30 cm) of all the landforms of the two areas. Data were collected through documentary studies, fieldwork, and laboratory analysis, and their spatial processing and statistical analysis were carried out with ArcGIS and SPSS 26 software, respectively.

Geographical location and characteristics of the study area

The study area is located in North Khorasan Province, in the common territory of Jajarm and Esfarayen counties, and includes Chehel-Dokhtaran and Miandasht of Jajarm. These two areas extend between 56°25′45″ and 57°8′30″ E and between 36°46′24″ and 37°2′22.5″ N (Figure 1). From the perspective of land management, these two sites have experienced distinct conditions because of different protection approaches: the Miandasht area, owing to its rich steppe vegetation and high habitat value, has been protected and managed by the Department of Environment since 1973 (1352 SH), and the continuous exclosures applied there have, in addition to controlling wind erosion, led to the ecological stability of the rangeland. In contrast, the lands of Chehel-Dokhtaran, which are part of the winter rangelands supervised by the Natural Resources Organization, have lacked protective restrictions and government exclosures for controlling livestock grazing in recent decades. This difference in management history and intensity of use has provided a suitable research setting for comparing the soil carbon sequestration potential under different land uses in these two areas. This research was carried out from April 2025 (Farvardin 1404 SH) to June–July 2026 (Tir 1405 SH).

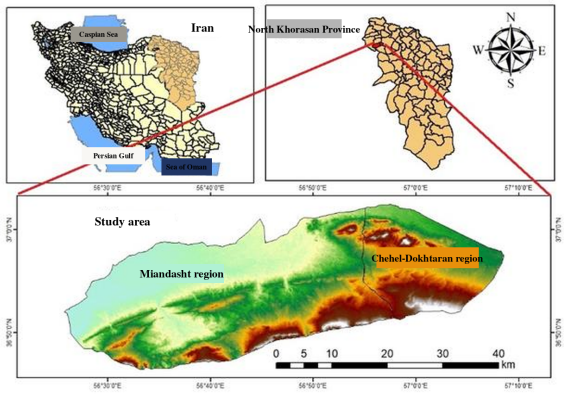

Figure 1) Geographical location of the study area (Miandasht of Jajarm and Chehel-Dokhtaran south of Esfarayen) in North Khorasan Province and Iran

Identification of landforms

To identify and delineate the geomorphological landforms of the area, Landsat 8 OLI satellite images from August 2022 (Mordad 1401 SH), the SRTM digital elevation model with a spatial resolution of 30 m, and topographic maps were integrated and interpreted, and the boundaries of the units (mountain, pediment, badland hills, sand dunes, clay–salt surfaces, floodplains, and alluvial terraces) were drawn in ArcGIS software. Documentary studies were also used to develop the theoretical foundations and review the background.

Sampling

Stratified random sampling was used to collect the data. For this purpose, by overlaying the layer of geomorphological units and the layer of management boundaries (the Miandasht protected area and the Chehel-Dokhtaran free area) in ArcGIS, a map of homogeneous strata was prepared. Accordingly, given the variety of geomorphic units and landforms, three replicates were considered in each area for the more extensive landforms and two replicates for the landforms with more limited extent and accessibility, namely the alluvial terrace and the mountain; as a result, a total of 38 sampling points (19 points in each area) were determined. The number of samples in each stratum was determined on the basis of the extent and accessibility of the landform, and each landform in each area was considered an independent group. Fieldwork was carried out using a Global Positioning System (GPS) device for navigating to the stations. At each station, soil samples from a depth of 0–30 cm (as the active surface horizon and the most concentrated layer for carbon exchange) were collected after removing the litter and packed in labeled plastic bags for transfer to the laboratory.

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Laboratory method

In the laboratory stage, the samples were air-dried, crushed, and passed through a 2 mm sieve to separate the coarse fraction. The Walkley–Black wet oxidation method was used, in accordance with standard instructions, to determine the soil organic carbon content. In this method, the organic carbon was oxidized in an acidic medium by a potassium dichromate solution, and the amount of oxidant consumed was measured by titration. Finally, after the percentage of organic carbon was calculated, the values obtained were used as the dependent variable in the statistical analyses.

Statistical analyses

Data analysis was carried out with SPSS 26 in three stages: checking the assumptions, fitting the generalized linear model (GzLM), and evaluating the fit and extracting the coefficients. First, the mean, standard deviation, and number of samples of soil organic carbon (percent) were calculated separately for the seven landforms in each area.

Before running the final model, the normality of the distribution of soil organic carbon in each area was examined with the Shapiro–Wilk test, and the presence of outliers was examined with box plots. To keep all 38 samples and to control the effect of extreme values, a robust estimator was used to correct the standard errors. The skewness of the data was 1.431 and the kurtosis 0.988, and their distribution was not normal. Therefore, given that the data were positive, skewed, and heterogeneous, a generalized linear model with a gamma distribution for the random component and a logarithmic link function for the systematic component was used as the main analytical framework, because this model avoids the limitations of traditional transformations (such as the logarithmic transformation) in interpreting the results [Nelder & Wedderburn, 1972; Ng & Cribbie, 2019]. The dependent variable was soil organic carbon (percent), and the independent variables were landform (seven levels), management status (two levels: protected and free), and their interaction. The validity of the model was examined with three criteria: the overall significance of the model against the baseline model with the likelihood ratio test; the ratio of model deviance and of Pearson chi-square to degrees of freedom to assess the dispersion of the data; and the Akaike and Bayesian information criteria for selecting the optimal model and preventing overfitting. In the final stage, the independent effects of landform and management status and their interaction on soil organic carbon were tested with the Wald chi-square test, and the model coefficients were estimated to determine the direction and strength of the effect of each landform.

Findings

On the basis of the geomorphological map, seven landforms were identified in Miandasht and Chehel-Dokhtaran: mountain, pediment, badland hills, sand dunes, clay–salt surfaces, floodplains, and alluvial terraces. The floodplains developed as relatively flat surfaces along the main channels and watercourses, especially at the margins of the Kal-Shur, and were formed from fine-grained silty and clayey sediments. The clay–salt surfaces were formed mainly from fine-grained clayey sediments with low permeability and, because they lie in low areas without adequate drainage, were subject to intense evaporation, so that salt and gypsum accumulated in their surface and subsurface layers (Figure 2).

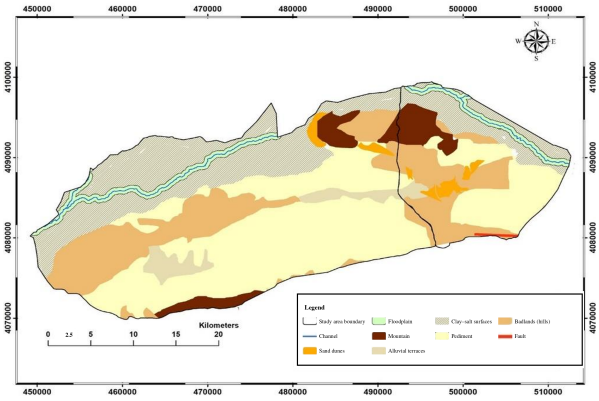

Figure 2) Geomorphological map (landforms) of Miandasht of Jajarm and Chehel-Dokhtaran south of Esfarayen

Soil organic carbon in the landforms and study areas

The mean soil organic carbon was 0.268% in Miandasht (protected) and 0.199% in Chehel-Dokhtaran (free management), and the mean of all 38 samples reached 0.234% (Table 1). In both areas, the floodplain had the highest organic carbon (Miandasht 0.739% and Chehel-Dokhtaran 0.529%), and its mean in the whole area was 0.634%; this value was nearly three times that of the clay–salt surfaces (0.236%), which ranked second. They were followed by the alluvial terraces (0.190%), sand dunes (0.178%), pediment (0.165%), and mountain (0.136%). The badland hills had the lowest organic carbon (0.055%), and their value was lower than that of all other landforms in both areas (Miandasht 0.042% and Chehel-Dokhtaran 0.068%).

Table 1) Mean soil organic carbon (percent) and number of samples (in parentheses) in the landforms of Miandasht of Jajarm (protected), Chehel-Dokhtaran south of Esfarayen (free management), and the whole area

Landform	Miandasht (protected)	Chehel-Dokht (free)	Whole area
Floodplain	0.739 (3)	0.529 (3)	0.634 (6)
Clay–salt surfaces	0.292 (3)	0.179 (3)	0.236 (6)
Alluvial terrace	0.238 (2)	0.143 (2)	0.190 (4)
Sand dunes	0.250 (3)	0.106 (3)	0.178 (6)
Pediment	0.146 (3)	0.177 (3)	0.165 (6)
Mountain	0.109 (2)	0.162 (2)	0.136 (4)
Badland hills	0.042 (3)	0.068 (3)	0.055 (6)
All landforms	0.268 (19)	0.199 (19)	0.234 (38)

The order of the landforms was largely similar, but

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differences were also observed. The organic carbon of the sand dunes in Miandasht (0.250%) was more than twice that in Chehel-Dokhtaran (0.106%), and the alluvial terraces (0.238% versus 0.143%) and clay–salt surfaces (0.292% versus 0.179%) also had higher values in Miandasht. In contrast, the mountain (0.162% versus 0.109%), pediment (0.177% versus 0.146%), and badland hills (0.068% versus 0.042%) had more organic carbon in Chehel-Dokhtaran.

Effect of landform and management status

Soil organic carbon did not have a normal distribution in either area; low values were more frequent, and a few very high values were also observed. Therefore, a generalized linear model with a gamma distribution was used. The final model fitted very well and, compared with the baseline model, explained the variation in soil organic carbon significantly.

The difference among the landforms in soil organic carbon was significant, and landform was the main factor in the variation of organic carbon. In contrast, the difference between the protected area and the free area, as well as the combined effect of landform and management, was not significant; that is, the higher mean of Miandasht was not statistically confirmed after the landform type was taken into account. However, the sand dunes were in a different situation, and their organic carbon had increased from 0.106% in Chehel-Dokhtaran to 0.250% in Miandasht. Because of the strong fluctuation of values in this landform and the relative stability of values in the other landforms, this local increase was not reflected in the overall results, and the combined effect of landform and management remained non-significant.

Discussion

The aim of this research was to examine the role of different landforms and geomorphological units in the distribution of soil organic carbon, with an emphasis on a comparative study between the Miandasht protected area of Jajarm and the unprotected Chehel-Dokhtaran area south of Esfarayen. According to the results obtained, there are significant differences in soil organic carbon among the studied landforms. The findings show that the spatial distribution of carbon in the area follows a structural and geomorphological pattern, such that the inherent characteristics of the landforms and the textural conditions of the soil have created natural limitations that management interventions and differences in protection status (exclosure versus overgrazing) have not been able to overcome at the macro scale. Accordingly, the potential of the lands of the area to retain and stabilize carbon can be divided into three main groups. In the first group, with high sequestration potential, the highest amount of carbon was recorded in the floodplain, a phenomenon consistent with its low geomorphological position, reduced slope gradient, continuous deposition of fine-grained sediments, and accumulation of water in these level alluvial zones. In this landform, hydrological conditions, the stability of soil moisture, and waterlogged and anaerobic conditions provide a favorable setting for the accumulation of organic matter and greatly reduce the rate of microbial decomposition. This similarity of behavior in both areas shows that the hydromorphic processes of the substrate operate independently of differences in the type of protective management. These results agree with the findings of Kamali and Sadeghipour, Babaei *et al.*, Scott and Wohl, and Alderson *et al.* [Kamali & Sadeghipour, 2018; Babaei *et al.*, 2016; Scott & Wohl, 2018; Alderson *et al.*, 2019].

In addition, the textural characteristics of the soil play a key role in the stability of this potential; finer-textured, clay-rich soils in these areas, through the formation of organo-mineral complexes, provide effective physical and chemical protection that ensures the persistence of carbon. This finding is consistent with the results of Babaei *et al.* and Shi *et al.* [Babaei *et al.*, 2016; Shi *et al.*, 2019]. In this regard, the findings of Yue *et al.* [Yue *et al.*, 2026] show that depositional landforms increase the share of mineral-associated organic carbon by 15% to 25% through the threefold mechanism of physical burial, the formation of stable chemical complexes, and anaerobic inhibition.

The next group comprises lands with moderate potential, among which the clay–salt surfaces rank second in carbon content, and the variation of organic carbon in them is influenced by two opposing controlling factors. On the one hand, the presence of the clay fraction, by providing physical protection and structural stability, enhances the ability to stabilize organic carbon, which is in line with the findings of Xiao and Janjani *et al.* [Xiao, 2015; Janjani *et al.*, 2022]. On the other hand, high salinity and the presence of evaporite minerals, by limiting vegetation and reducing the input of organic matter to the soil, have prevented this landform from reaching the level of the floodplain. This interpretation is consistent with the findings of Zarrinkafsh *et al.* [Zarrinkafsh *et al.*, 2016]. The alluvial terraces of the area ranked third in carbon sequestration among the studied landforms, which indicates a relatively suitable capacity of these lands for storing soil organic carbon. This situation is consistent with the geomorphic position of the terraces and their physical capacity to accumulate fine-grained sediments. However, the increase in concentrated rainfall intensifies the leaching and physical displacement of organic carbon from the surface soil of the terraces and alluvial surfaces; on the other hand, hydrological fluctuations, together with temperature changes, reduce aggregate stability and accelerate the microbial decomposition of organic compounds [Wang *et al.*, 2025].

The next landform in this group was the sand dunes, zones that faced a marked loss of organic carbon because of aeolian processes and substrate instability. In this landform, the coarse texture and the lack of fine particles prevent the formation of stable organo-mineral bonds

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and, together with wind erosion, accelerate the rapid removal of carbon from the system. These findings are consistent with the results of previous research [Xiao, 2015; Mo *et al.*, 2024]. However, the evidence showed that this landform responded rapidly and positively under exclosure and the removal of livestock grazing; vegetation recovered in patches and locally increased soil organic carbon at these points. In this pattern of recovery, the vegetation of the sand dunes grows irregularly and in patches, which leads to the formation of "islands of fertility". This phenomenon creates high variability in the soil carbon data of this landform and shows that local factors and patchy vegetation have a greater influence than the general, large-scale characteristics of the area [Stover *et al.*, 2025]. After the sand dunes, the pediment unit was placed in this group. This position is due to the location of the pediment between the mountain and the floodplain, so that it mostly plays the role of an erosional and transitional zone. The topographic characteristics of this landform cause intense desert downpours to easily wash away the fine particles and organic matter of the surface soil and carry them to downstream areas. This process of erosion and non-stabilization of sediments has caused the organic carbon in the surface soil of the pediment not to accumulate to high levels and to remain at a moderate level, because water flows are continuously moving the carbon of these surfaces toward the lowlands. This hydraulic mechanism has also been confirmed in other research [Hirmas *et al.*, 2010].

In addition to these, the mountain landform was also placed in this group with moderate potential; the findings of this research showed that, because of topographic instability, steep slopes, and intense mechanical erosion, the mountain landform faces serious limitations in soil profile development and reduced organic carbon stocks. This pattern of carbon poverty, which is intensified by the washing of surface horizons, agrees with the results of previous research [Noormohammadi & Esmailzadeh, 2015; Falahatkar *et al.*, 2014; Buraka *et al.*, 2022]. A distinctive feature of these lands is that the distribution of carbon does not follow a simple linear relationship with increasing elevation; rather, it is the result of the complex interaction of local components such as slope, soil moisture conditions, and erosion intensity. This nonlinear and multifactorial behavior of the carbon cycle in mountain environments had also been confirmed previously [Heidari *et al.*, 2010; Jafarian & Ghorbani, 2024].

At the lowest rank, the badland hills landform had the lowest carbon sequestration potential; this situation is the direct result of intense slope erosion, the washing away of fine particles, and the dominance of physical processes over the biological capacity of the soil. In this landform, steep slopes cause creep and surface washing of the soil [Palmtag *et al.*, 2018], a process that agrees with the field findings of Miri *et al.* [Miri *et al.*, 2025] and the studies of Yue *et al.* [Yue *et al.*, 2026]. These researchers showed that, because of their convex longitudinal curvature, badland slopes accelerate the velocity of runoff and the loss of organic carbon. In addition, the experimental studies of Lasanta *et al.* [Lasanta *et al.*, 2021] on marl formations show that, because of the poverty of organic matter and weak vegetation, water infiltration in these lands decreases and the runoff generation capacity of the slopes increases. These conditions expose the soil to intense erosion and create deep rills and gullies on the slopes. Continuous erosion also causes the removal of fine clay and silt particles from the soil. As a result, this intense hydrological washing, by depleting the surface horizon and the nutrient-rich substrate, has destroyed the natural capacity of the badland landform to store and stabilize organic matter and has weakened the ecological stability of the soil, such that even protective measures and medium-term exclosure have had no significant effect on improving carbon sequestration in the badland landforms. This lack of influence of management differences is in line with the findings of other researchers [Wang *et al.*, 2025; Lin *et al.*, 2026], because applying medium-term grazing restrictions (less than two decades) in fragile desert ecosystems has little effect on the organic carbon stock of the soil. Moreover, the findings of Lin *et al.* [Lin *et al.*, 2026] show that even if vegetation apparently recovers as a result of exclosure, this improvement is not simultaneously reflected in the biogeochemical changes of the subsurface soil, a phenomenon known as "soil–plant response decoupling". Accordingly, creating stable and significant changes in the soil carbon sequestration of these lands requires the continuation of exclosure over very long periods, exceeding three decades. Therefore, the dominance of the inherent and geomorphological characteristics of landforms as the main factor in the distribution of carbon has meant that protective measures alone cannot overcome these natural limitations in erosional units.

The difference in carbon sequestration capacity among the various landforms shows that landform type plays a key role in the variation of soil organic carbon and makes it necessary to design management measures in a landform-based way. Accordingly, management programs are prioritized on the basis of the inherent capacity of landforms; the landforms with the highest potential for carbon storage, namely the floodplains and, after them, the clay–salt surfaces and alluvial terraces, are the first priority for special protection. Among these, lowland zones such as floodplains, because of their much higher capacity for stabilizing carbon, require complete exclosure of the land, and any construction or excessive use that disturbs the surface structure of the soil is prohibited or restricted in them, because the preservation of these substrates ensures the continuity of the carbon sequestration cycle in the area. In the badland hills and mountains, where erosion overrides sequestration capacity, soil and water conservation measures such

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as runoff control and avoidance of plowing along the slope are more appropriate than exclosure alone. In the sand dunes, where organic carbon has increased under exclosure, the continuation of exclosure and the patchy restoration of vegetation are recommended.

This research was carried out with 38 samples (two or three samples in each landform and area) and only at a depth of 0–30 cm, and soil texture and bulk density were not measured; therefore, generalizing the results to landforms with few samples, such as the sand dunes, and estimating soil carbon stocks require caution. It is suggested that future research be carried out with more samples, multiple depths, measurement of soil texture and bulk density, and long-term monitoring of the effect of exclosure on carbon sequestration, especially in the sand dunes.

Conclusion

The spatial distribution of soil organic carbon in Miandasht of Jajarm and Chehel-Dokhtaran south of Esfarayen follows the structural characteristics of the landforms. The depositional floodplain landforms have the highest and the erosional badland hills with marl formations the lowest organic carbon. Medium-term protective management (exclosure) has no significant effect on the overall pattern of carbon distribution, and erosional processes override sequestration capacity. Therefore, the management of carbon sequestration should be designed on the basis of landforms.

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