Rapid depletion of soil organic carbon stock threatens agricultural sustainability in Iran

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2026-07-16

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Abstract

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Full Text

J Arid Land (2026) 18(7): 1179–1191
doi: 10.1016/j.jaridl.2026.05.012; CSTR: 32276.14.JAL.20250666

Rapid depletion of soil organic carbon stock threatens agricultural sustainability in Iran

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Abstract: Soil organic carbon (SOC) stocks play a critical role in maintaining soil fertility, regulating biogeochemical cycles, and mitigating climate change, yet they are increasingly threatened in semi-arid agricultural regions. This study quantified spatiotemporal changes in SOC concentration and stocks across Hamadan Province, western Iran, over a 16-a period (2010–2025), a region that has undergone rapid agricultural intensification. A total of 212 soil samples were collected from the same georeferenced locations during both sampling campaigns, targeting the 0–30 cm soil layer. SOC concentration was determined using standardized laboratory methods, and SOC stock was calculated by integrating SOC concentration, bulk density, soil depth, and coarse fragment content. Geostatistical analyses, including experimental semivariograms and Ordinary Kriging, were applied to characterize spatial variability and to generate continuous maps of SOC concentration and SOC stock for both years (2010 and 2025). Results indicated a marked decline in mean SOC concentration, from 0.99% in 2010 to 0.85% in 2025. Correspondingly, mean SOC stock decreased from 126.48 to 84.45 Mg C/hm2, representing a reduction of 33.23% and a total carbon loss of approximately 4.59 Tg C from agricultural topsoil across the province. Spatial analysis revealed increased micro-scale variability and extended spatial dependence over time, reflecting increasingly heterogeneous management effects superimposed on broader landscape controls. Severe SOC stock depletion (SOC stock ratio (the ratio of SOC stock in 2025 to that in 2010) <0.50) occurred as scattered patches across the province, while moderate declines (0.50–1.00) dominated most agricultural areas, and some northern and southern zones showed comparatively greater stability or localized carbon gains. This study provides the first long-term, spatially explicit assessment of SOC stock dynamics in western Iran, demonstrating rapid carbon depletion driven by intensive cultivation under semi-arid conditions. The findings highlight the urgent need for soil conservation and carbon-preserving management practices to sustain soil health, agricultural productivity, and climate mitigation potential in dryland farming systems.

Keywords: soil organic carbon; carbon loss; agroecosystems; Ordinary Kriging; experimental semivariograms; Hamadan Province

Citation: Mehdi NOURZADEH HADAD, Jose Antonio RODRIGUEZ MARTIN, Akbar HASSANI. 2026. Rapid depletion of soil organic carbon stock threatens agricultural sustainability in Iran. Journal of Arid Land, 18(7): 1179–1191. https://doi.org/10.1016/j.jaridl.2026.05.012; https://cstr.cn/32276.14.JAL.20250666

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Received 2025-12-30; revised 2026-04-18; accepted 2026-05-14

KeAi Communications Co. Ltd.

http://jal.xjegi.com; https://www.keaipublishing.com/en/journals/journal-of-arid-land/

This version posted 2026-07-16.

1 Introduction

Soil organic carbon (SOC) plays a fundamental role in regulating soil structure, nutrient cycling, and water retention, while also constituting one of the largest terrestrial carbon reservoirs relevant to climate change mitigation (Lal et al., 2011; Aguilera et al., 2013; Batjes, 2014; Jebari et al., 2018; Takoutsing and Martín, 2025). As a central indicator of soil health, SOC directly influences ecosystem productivity, crop resilience, and long-term agricultural sustainability (Tor-Gunnar and Leigh, 2013; Álvaro-Fuentes et al., 2014; Takoutsing et al., 2016; van den Hoogen et al., 2019). Globally, widespread conversion of natural ecosystems to croplands, combined with intensive and often unsustainable agricultural practices, has resulted in substantial historical losses of SOC stock, contributing significantly to increased atmospheric CO_2 concentrations (Chen et al., 2018; Rodríguez Martín et al., 2019). Numerous studies now document persistent SOC decline across a wide range of agroecosystems worldwide, particularly in regions under long-term intensive management (e.g., Wang et al., 2025).

In temperate agricultural systems, long-term experiments have shown that reduced tillage does not necessarily increase SOC stock, although it may modify their vertical distribution within the soil profile (Apostolakis et al., 2026). Nonetheless, the global soil carbon reservoir within the upper meter of soil represents a major opportunity for climate change mitigation, making SOC sequestration in agricultural lands a central objective of international initiatives such as "4 per 1000" Initiative (Paustian et al., 2000). Achieving this objective, however, remains particularly challenging in semi-arid environments, where climatic constraints and rapid organic matter mineralization limit the capacity for carbon accumulation.

Iran provides a compelling case study of these challenges due to its wide range of climatic zones and rapid land-use change. In the humid northern regions, conversion of forests to croplands has resulted in pronounced SOC losses. For example, Falahatkar et al. (2014) reported a decline of SOC from 6.70 to 3.20 kg C/m^2 in the upper 20 cm following deforestation, representing a loss exceeding 50.00%. In contrast, semi-arid regions are inherently more vulnerable to SOC stock depletion due to limited precipitation, high evaporation rates, and sparse biomass inputs (Deng et al., 2018). In western Iran with semi-arid climate, Ayoubi et al. (2012) demonstrated that forest-to-cropland conversion reduced SOC within macroaggregates, thereby weakening soil structural stability, particularly on sloping landscapes prone to erosion. Similar trends have been observed in southwestern Iran, where conversion of forest and pasture to cropland substantially reduced both labile and total SOC pools, with labile fractions being especially sensitive to disturbance (Geraei et al., 2016).

National-scale assessments further confirm the severity of SOC stock depletion in Iranian agricultural systems. Rezaei et al. (2022) reported that only 4.00% of croplands in Iran contain more than 2.00% SOC concentration, while the majority have SOC concentrations below 1.00%. In central Iran, semi-arid loess soils under continuous wheat cultivation typically contain 1.00%–1.50% SOC concentration based on regional case studies (Ayoubi et al., 2012; Nourzadeh et al., 2012), declining to less than 1.00% after prolonged conventional tillage. In southern Iranian irrigated systems, SOC concentrations frequently fall below 0.50% (Geraei et al., 2016), indicating an even more advanced level of degradation. These findings collectively demonstrate that SOC stock depletion is pervasive across Iranian agroecosystems, though the magnitude is modulated by climate, land use, and management intensity. Recent research increasingly integrates legacy soil inventories with geospatial techniques to analyze SOC dynamics at regional to global scales. Spatiotemporal modelling study shows that SOC changes are highly heterogeneous, driven by interacting effects of climate, topography, land use, and management, with croplands typically exhibiting lower and more variable SOC than forests and grasslands (Xiang et al., 2025). Digital soil mapping approaches have become particularly valuable for detecting spatial patterns of SOC change, although their effectiveness can be constrained in drylands by strong inherent spatial variability and relatively small temporal trends (von Fromm et al., 2025; Zhao et al., 2025).

Hamadan Province, a major cereal-legume production region in western Iran, exemplifies these challenges. Over recent decades, the region has experienced rapid agricultural intensification characterized by expanded irrigation, increased mechanization, continued reliance on traditional tillage systems, and growing dependence on mineral fertilizers. These pressures are superimposed on broader climate change signals, including rising temperatures and increased drought frequency, which together are likely to have altered carbon inputs, decomposition rates, and erosion processes. Despite its agricultural importance, long-term, spatially explicit assessments of SOC stock in Hamadan Province remain scarce.

This study provides a long-term, province-scale, spatially explicit quantification of SOC stock dynamics in western Iran. By integrating repeated field measurements with geostatistical analysis, it offers new insights into the rates, spatial patterns, and drivers of SOC stock depletion in semi-arid croplands, informing both regional soil management strategies and national carbon conservation policies. Accordingly, the objectives of this research were to: (1) quantify and map the spatial distributions of SOC concentration and SOC stock across Hamadan Province' s agricultural lands using geostatistical methods; and (2) analyze spatiotemporal changes in SOC stock over a 16-a period (2010–2025) to assess the combined impacts of agricultural intensification and environmental change. The findings contribute to a better understanding of SOC stock depletion processes in semi-arid agroecosystems and provide a scientific basis for designing soil conservation and sustainable land management strategies in dryland regions.

2 Materials and methods

2.1 Study area and regional agricultural context

Hamadan Province is located in western Iran between approximately 34°05′–35°45′N and 47°55′–49°30′E. The region is characterized by a semi-arid climate with cold winters and dry, warm summers. Mean annual precipitation ranges from 300 to 400 mm, with most precipitation occurring during winter and early spring. Soils in the study area have developed predominantly on calcareous parent materials and are mainly distributed across extensive alluvial and loess-derived plains. Agriculture in Hamadan Province is dominated by rain-fed and irrigated cereal-legume systems, primarily wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and chickpea (*Cicer arietinum* L.). Over recent decades, the region has experienced marked agricultural intensification, including increased groundwater extraction for irrigation, expanded cropped area, and the widespread use of conventional tillage practices, raising concerns regarding soil degradation and long-term sustainability (Mesgaran et al., 2017; Shahnawaz et al., 2019).

To contextualize observed changes in SOC, we compiled regional agricultural management trends between 2010 and 2025 from official statistics and published sources. According to the Agricultural Jihad Organization of Hamadan (2025), total synthetic fertilizer consumption increased by approximately 25.00% over the study period (2010–2025), with nitrogen fertilizer application rising from 85 to 106 kg/hm^2. The area under irrigated croplands expanded by about 15.00%, from 0.120×10^{6} to 0.138×10^{6} hm^2, largely driven by groundwater extraction. Conventional tillage systems remained dominant throughout the period, with more than 90.00% of farmers using mouldboard ploughs for primary tillage operations (Agricultural Jihad Organization of Hamadan, 2025). These regional trends are consistent with national patterns of agricultural intensification reported for Iran (Mesgaran et al., 2017) and provide an essential context for interpreting spatiotemporal changes in soil properties.

2.2 Soil sampling and laboratory analyses

Soil sampling campaigns were conducted in 2010 and 2025 at the same predefined, georeferenced locations to ensure strict temporal comparability. A total of 212 sampling sites were distributed across agricultural lands of Hamadan Province (Fig. 1). At each site, five subsamples were collected from the 0–30 cm soil layer using an auger and composited to form a representative

sample of approximately 3 kg (Nourzadeh et al., 2012; Nourzadeh Haddad et al., 2013).

Soil samples were air-dried and sieved through a 2-mm mesh prior to laboratory analysis. Particle size distribution was determined using the hydrometer method after removal of organic matter with hydrogen peroxide and dispersion with sodium hexametaphosphate. We calculated sand (50–2000 μm), silt (2–50 μm), and clay (<2 μm) fractions based on sedimentation times (Day, 1965). Bulk density (BD) and total porosity were measured in laboratory using undisturbed soil cores sampled in the field by the core method (Blake and Hartge, 1986). The volumetric percentage of coarse particles (>2000 μm, including gravel and rock fragments) was subsequently used in the calculation of SOC stock.

Fig. 1 Spatial distribution of soil sampling sites across administrative agricultural lands in Hamadan Province

SOC concentration was determined via the Walkley-Black wet oxidation method (Walkley, 1935). Soil pH and electrical conductivity (EC) were measured potentiometrically in a 1.0:2.5 soil-to-water suspension. Available phosphorus (AP) was extracted using the Olsen method and quantified colorimetrically. Exchangeable potassium (EK) was extracted with 1 mol/L ammonium acetate (NH4OAc) and measured by flame photometry. Inorganic nitrogen fractions-nitrate (NO_3^-) and ammonium (NH_4^+) were extracted with 2 mol/L potassium chloride (KCl) and analyzed via colorimetric flow injection analysis.

2.3 SOC stock calculation

SOC stock (Mg C/hm^2) was calculated for the 0–30 cm layer using the established equation (Muñoz-Rojas et al., 2012; Rodríguez Martín et al., 2016):

$$\text{SOC stock} = \text{SOC} \times \text{BD} \times D \times (1 - S) \times 100, \quad (1)$$

where SOC is the soil organic carbon concentration (%); BD is the bulk density (g/cm^3); D is the soil layer thickness (30 cm); and S is the volumetric coarse fragment fraction (%).

2.4 Statistical and geostatistical analyses

Descriptive statistics were calculated for all soil parameters. Temporal changes in SOC concentration and related soil parameters between 2010 and 2025 were evaluated using a paired-sample t-test applied to collocated observations. This approach accounts for repeated measurements at identical sampling sites. Given that classical statistical tests assume independence of observations—this assumption may be violated in spatially structured soil

datasets—t-test results were interpreted with caution (Rodríguez Martín et al., 2009; Nanos et al., 2015). Geostatistical analyses were applied to explicitly evaluate spatial dependence. Experimental semivariograms were computed to characterize spatial autocorrelation of SOC, BD, and stoniness. Semivariograms were calculated as follows (Goovaerts, 1997):

$$\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} \left[Z(u_i) - Z(u_i + h)\right]^2, \tag{2}$$

where $\gamma(h)$ is the semivariance at lag distance h; $n(h)$ is the number of paired observations at distance h; and $Z(u_i)$ and $Z(u_i+h)$ are the values of the variable at locations u_i and $u_i + h$, respectively, which are separated by a lag distance h. The factor $1/2$ ensures that $\gamma(h)$ equals the variance of $Z(u_i)$ when h is sufficiently large (i.e., beyond the range of spatial autocorrelation).

Experimental semivariograms were fitted with exponential models to determine the nugget, sill, and range parameters. Ordinary Kriging was subsequently applied to interpolate SOC, BD, and stoniness values across the study area. Kriging estimates at an unsampled location $R(u)$ were computed as a weighted sum of nearby observations:

$$R(u) = \sum_{j=1}^{j=m} \lambda_j Z(u_j), \tag{3}$$

where j is an index representing each of the m neighboring data points used in the estimation; λ_j is the Kriging weight assigned to the j^{th} neighboring observation; and $Z(u_j)$ is the value of the variable at location u_j.

Kriging predictions were assessed by leave-one-out cross-validation. Prediction accuracy was evaluated using root mean square error (RMSE) and standard prediction errors. All statistical analyses were performed using XLSTAT (version 2024.1; Addinsoft, Paris, France), IsatisNeo (version 2022.2; Geovariances, Fontainebleau, France), and ArcGIS Desktop (version 10.8; Esri, Redlands, USA).

3 Results and discussion

Regional agricultural statistics indicated that Hamadan Province experienced marked intensification of agricultural practices between 2010 and 2025, including increased fertilizer inputs, expansion of irrigated area, and continued reliance on conventional tillage systems (Agricultural Jihad Organization of Hamadan, 2025). Although site-specific management data were not available for individual sampling sites, these documented trends provided a robust contextual framework for interpreting soil property changes. In particular, the concurrent increases in soil EC and plant-available nutrients (e.g., AP and EK) were consistent with intensified mineral fertilization and irrigation practices, which are widely associated with SOC stock depletion under semi-arid conditions. Nevertheless, other factors, including climate variability and regional warming trends, may also have contributed to SOC dynamics over the study period.

3.1 Temporal changes in SOC concentration, SOC stock, and other soil properties

Descriptive statistics for main soil properties in 2010 and 2025 are summarized in Table 1. Over the study period, SOC status showed clear deterioration across the agricultural lands of Hamadan Province. Mean SOC concentration declined from 0.99% in 2010 to 0.85% in 2025. A paired-sample t-test applied to collocated observations indicated that this decline was statistically significant ($t = 3.12$, $P = 0.002$). Although spatial autocorrelation may have influenced the degrees of freedom, the magnitude and spatial consistency of the decline strongly supported the existence of a real temporal trend.

Median SOC concentration exhibited a similar decreasing trend from 0.92% to 0.79%, placing the majority of samples at or below the widely cited 1.00% SOC threshold—a level associated with soil structural stability and reduced biological activity in semi-arid agroecosystems (Loveland and Webb, 2003). This shift indicated that a large proportion of agricultural soils in Hamadan Province now fall into a low-carbon status category. Consistent with changes in SOC

concentration, mean SOC stock (0–30 cm) declined markedly from 126.48 Mg C/hm^2 in 2010 to 84.45 Mg C/hm^2 in 2025, corresponding to a net loss of 42.03 Mg C/hm^2 and an overall reduction of 33.23% in topsoil organic carbon stocks across the province (Table 2). In absolute terms, this represented a carbon loss of 4.59 Tg C from agricultural soils in Hamadan Province over a 16-a period, indicating rapid SOC stock depletion of a critical ecological asset.

Table 1 Statistical summary of descriptive soil properties in 2010 and 2025

Soil property	Year	Mean	Median	Minimum	Maximum	SD
BD (g/cm^3)	2010	1.42	1.41	1.12	1.68	0.11
BD (g/cm^3)	2025	1.48	1.47	1.18	1.75	0.12
SOC concentration (%)	2010	0.99	0.92	0.02	3.40	0.50
SOC concentration (%)	2025	0.85	0.79	0.00	3.31	0.50
Sand (%)	2010	33.50	32.00	17.00	76.00	13.80

Soil property	Year	Mean	Median	Minimum	Maximum	SD
Sand (%)	2025	33.66	32.00	18.00	75.00	14.00
Silt (%)	2010	38.60	38.00	12.00	61.00	9.50
Silt (%)	2025	38.10	38.00	12.00	62.00	9.40
Clay (%)	2010	28.00	30.00	9.00	48.00	7.60
Clay (%)	2025	28.60	29.40	8.00	48.00	7.50
NO_3^- (mg/kg)	2010	13.09	9.59	1.32	96.70	11.98
NO_3^- (mg/kg)	2025	17.20	12.24	1.98	128.93	15.69
NH_4^+ (mg/kg)	2010	1.58	1.32	0.00	7.05	1.18
NH_4^+ (mg/kg)	2025	2.11	1.76	0.11	9.05	1.50
pH	2010	7.59	7.60	6.50	8.30	0.23
pH	2025	8.07	8.09	6.93	8.85	0.25
EC (dS/m)	2010	1.23	0.87	0.34	10.20	1.23
EC (dS/m)	2025	1.64	1.13	0.41	13.60	1.66
AP (mg/kg)	2010	11.90	8.48	1.60	75.60	11.27
AP (mg/kg)	2025	15.03	10.60	1.92	90.72	14.35
EK (mg/kg)	2010	327.16	290.00	70.00	1000.00	169.00
EK (mg/kg)	2025	425.44	378.67	93.33	1250.00	216.72

Note: BD, bulk density; SOC, soil organic carbon; EC, electrical conductivity; AP, available phosphorus; EK, exchangeable potassium; SD, standard deviation.

Table 2 SOC stock at the 0–30 cm depth in 2010 and 2025

Year	SOC stock (Mg C/hm^2): Mean	SOC stock (Mg C/hm^2): Minimum	SOC stock (Mg C/hm^2): Maximum	SOC stock (Mg C/hm^2): SD	Amount of carbon (Tg C)
2010	126.48	17.35	400.51	12.15	34.41
2025	84.45	4.05	328.01	9.63	29.82
Change (from 2010 to 2025)	−42.03	−13.30	−72.50		−4.59

Other soil properties exhibited changes symptomatic of agricultural intensification (Table 1). Soil pH increased from 7.59 to 8.07, suggesting progressive alkalization, which can negatively influence nutrient availability and SOC stabilization mechanisms (Takoutsing et al., 2016). Soil EC rose from 1.23 to 1.64 dS/m, indicating increasing salinity pressure, likely associated with irrigation water quality and reduced leaching efficiency (Mesgaran et al., 2017). Soil nutrient concentrations also increased substantially between 2010 and 2025. Inorganic nitrogen fractions increased substantially: mean NO_3^- rose from 13.09 to 17.20 mg/kg and NH_4^+ from 1.58 to 2.11 mg/kg. AP and EK also increased significantly. Similar patterns have been reported in Mediterranean and semi-arid agroecosystems, where high synthetic nitrogen and phosphorus inputs combined with residue removal accelerate SOC decline unless compensated by substantial organic amendments or conservation tillage (Lugato et al., 2014; García-González et al.,

2018). Collectively, these trends reflected a shift toward fertilizer-intensive systems characterized by limited organic matter return, resulting in nutrient-rich but carbon-poor soils (Álvaro-Fuentes et al., 2009; Chen et al., 2018).

The magnitude of SOC stock loss (42.03 Mg C/hm^2) observed in Hamadan Province is large when compared with other Mediterranean and semi-arid studies. For example, on Mallorca Island, Spain, Rodríguez-Martín et al. (2019) reported an overall 15.00% increase in agricultural SOC stock over a 11-a period, largely driven by abandonment of marginal terraces and grassland expansion, although intensively managed annual croplands within that study still experienced a 14.50% decrease. In many temperate regions under conventional tillage, decadal SOC stock changes are more typically in the range from −20.00% to −5.00%, depending on initial SOC stock levels, climate, and management intensity (Lugato et al., 2014; Jebari et al., 2018). Against this background, the 33.23% SOC stock loss observed in Hamadan Province during 2010–2025 places this region at the upper end of reported decline rates, especially given that all sampling sites correspond to continuously cultivated croplands.

Comparison with other regions of Iran further situates Hamadan Province within a broader national context of SOC stock depletion. In the humid northern provinces (e.g., Mazandaran and Guilan), forest soils contain high SOC stock (67.00 Mg C/hm^2), which are reduced by approximately 50.00% following conversion to croplands (Falahatkar et al., 2014). Although absolute SOC stock in Hamadan Province was lower due to its semi-arid climate, the relative magnitude of SOC stock depletion observed (approximately 33.23%) followed a comparable trajectory of land-use impact. Studies from western Iran (e.g., Lorestan and Kermanshah) reported declines in SOC concentrations within macroaggregates from approximately 1.50% to 0.90% following forest-to-cropland conversion (Ayoubi et al., 2012), closely mirroring the decline observed in Hamadan Province from 0.99% to 0.85%. In southwestern Iran (such as Khuzestan), intensively cultivated croplands typically exhibit SOC concentrations of 0.70%–0.90% (Geraei et al., 2016), a range consistent with current levels in Hamadan Province. A national survey corroborates this pattern, indicating that only 4.00% of Iranian croplands contain more than 2.00% SOC concentration, whereas the majority fall below 1.00% (Rezaei et al., 2022). The current SOC levels in Hamadan Province therefore appear representative of intensively cultivated semi-arid croplands across Iran. Together, these comparisons indicate that the observed SOC stock depletion in Hamadan Province is not an isolated phenomenon but rather forms part of a widespread national trend driven by agricultural intensification under moisture-limited conditions.

3.2 Spatial variability and spatiotemporal changes in SOC concentration

Geostatistical analysis revealed pronounced changes in the spatial structure and spatial distribution of SOC concentration between 2010 and 2025, reflecting the combined influence of agricultural intensification and broader landscape controls. Experimental semivariograms for both sampling years were best fitted by spherical models (Fig. 2), indicating a well-defined spatial dependence of SOC concentration in the study area. In 2010, SOC concentration exhibited a nugget of 0.54, a sill of 0.71, and a spatial dependence range of about 5.10 km under a spherical model (Fig. 2). This variogram structure indicated moderate micro-scale variability and suggested that SOC concentration distribution was largely governed by landscape-scale factors such as soil type, physiography, and long-term land-use patterns. The relatively shorter range implied that SOC spatial correlation weakens beyond a few kilometers, consistent with a heterogeneous agricultural landscape shaped by variable management intensity and environmental conditions. By 2025, clear modifications in variogram parameters were observed. The nugget increased to 0.92, indicating enhanced micro-scale variability and stronger fine-scale contrasts in SOC concentrations that were not fully captured at the sampling resolution. Such an increase is commonly associated with intensified and spatially heterogeneous management practices, including uneven residue return, patchy fertilizer application, localized erosion processes, and variability in tillage intensity (Morell et al., 2011; Chen et al., 2018). At the same time, the spatial dependence range expanded to approximately 7.60 km (Fig. 2), indicating that SOC spatial

correlation extended over broader distances compared with 2010.

The simultaneous increase in nugget variance and extension of spatial dependence range in 2025 compared with 2010 suggested a reorganization of SOC controls over time. While small-scale heterogeneity intensified due to localized anthropogenic disturbance (Cambardella et al., 1994; Nanos and Rodríguez Martín, 2012; Nanos et al., 2015), this was likely driven by widespread adoption of similar cropping systems, conventional tillage practices, and mineral fertilization regimes across large areas (Pardo et al., 2016; Paustian et al., 2019). This combination of processes is characteristic of intensively managed agroecosystems in semi-arid and Mediterranean environments, where human activities progressively override natural soil-forming factors as dominant drivers of SOC spatial patterns (Álvaro-Fuentes et al., 2008; García-González et al., 2018).

Cross-validation results (Table 3) indicated that the Ordinary Kriging interpolation provides a robust representation of SOC concentration spatial variability in both sampling years. RMSE values close to unity confirmed unbiased SOC concentration predictions and an appropriate estimation of Kriging uncertainty, supporting the reliability of the generated SOC concentration maps (Oliver and Webster, 2014). These validation results provided confidence that the mapped SOC concentration patterns faithfully reflect the underlying spatial organization of SOC concentration across the study area and form a sound basis for analyzing subsequent changes in SOC stock.

Spatial distribution maps of SOC concentration further supported these interpretations (Fig. 3). In 2010, SOC concentration exhibited a heterogeneous spatial pattern, with the highest values (1.50%–2.00%) located primarily in the western part of the province (Fig. 3a), functioning as an important reservoir of soil fertility. The central plains were dominated by low SOC concentration classes (0.50%–1.00%), interspersed with localized patches of higher concentration, while the northern, southern, southwestern, and northeastern parts already displayed a mixture of low to medium SOC concentration classes (0.50%–1.50%). This pattern suggested an agricultural landscape that, although still functionally diverse, was increasingly vulnerable to degradation (Post and Kwon, 2000; Poeplau and Don, 2015; Takoutsing et al., 2016).

Fig. 2 Experimental and model variograms for soil organic carbon (SOC) concentration in 2010 (a) and 2025 (b). Notable changes in spatial structure parameters were observed between the two sampling years.

Table 3 Cross-validation indices for Ordinary Kriging interpolation of SOC concentration

Year	Mean prediction error (%)	Average standard error (%)	RMSE (%)	Standardized RMSE
2010	−0.000532	1.486	1.554	1.008
2025	0.000203	1.477	1.504	1.024

Note: RMSE, root mean square error.

Fig. 3 Spatial distribution of SOC concentration across Hamadan Province in 2010 (a) and 2025 (b)

By 2025, the SOC concentration distribution shifted markedly towards a more homogeneous and depleted state (Fig. 3b). High-SOC patch in the western part had largely disappeared, and the central plains transitioned from predominantly medium SOC levels to dominance by low SOC classes (0.50%–1.00%). The eastern part of the province evolved into an extensive zone of very low SOC, and new low SOC areas emerged in central and interior regions (<0.50%). This convergence towards depleted SOC concentration classes was consistent with the observed increase in nugget variance and reflected both widespread SOC loss and increasing spatial fragmentation of soil quality. Comparable downward shifts in SOC concentration class distribution have been reported for intensively cultivated semi-arid regions, where prolonged tillage, residue removal, and insufficient organic inputs progressively erode the SOC pools (Álvaro-Fuentes et al., 2009; Chen et al., 2018; Han et al., 2022).

3.3 Spatiotemporal dynamics of SOC stock

Spatial patterns of SOC stock derived from kriged SOC concentration, BD, and coarse fragment content revealed pronounced spatiotemporal changes across Hamadan Province between 2010 and 2025 (Fig. 4). In 2010, SOC stock exhibited a heterogeneous spatial distribution, with extensive areas of moderate to high carbon stocks (150.00-200.00 Mg C/hm^2 or higher) concentrated primarily in the central and western parts of the province (Fig. 4a). These areas formed a contiguous belt that represented the core SOC reservoir of Hamadan Province's agricultural landscape, while lower SOC stock values (<100.00 Mg C/hm^2) represented a small area in the plains. This spatial configuration is characteristic of semi-arid agricultural regions where historical land use, soil properties, and topographic controls still exert a strong influence on SOC stock distribution (Post and Kwon, 2000; Poeplau and Don, 2015).

By 2025, this spatial configuration had changed markedly (Fig. 4b). The previously continuous belt of moderate-to-high SOC stock fragmented into a mosaic dominated by lower classes (<100.00 and 100.00–150.00 Mg C/hm^2). Central plains that had formerly functioned as the SOC stock "heartland" of the province experienced widespread downgrades to low SOC stock categories, indicating substantial carbon loss. In the northern and northeastern parts, areas that previously exhibited very high SOC stock (200.00–250.00 Mg C/hm^2 or higher) weakened considerably and became increasingly surrounded by expanding zones of lower SOC stock classes. Although the western and southwestern parts remained relatively richer in SOC stock compared with the rest of the province, these areas also showed clear declines from very high to moderate SOC stock classes. Only a small area of the central east zone has seen its SOC stock increase above 250 Mg C/hm^2 (Fig. 4b). Quantitative analysis confirmed these spatial trends (Table 2). From 2010 to 2025, mean SOC stock (0–30 cm) declined by 42.03 Mg C/hm^2 (33.23%), from 126.48 to 84.45 Mg C/hm^2. Across the agricultural lands in Hamadan Province, this equated to a net carbon loss of approximately 4.59 Tg C, underscoring substantial SOC stock depletion

under sustained intensive cultivation. This rate of SOC stock decline (33.23%) is high in comparison with many reported Mediterranean and temperate agroecosystems, where decadal reductions typically range between 5.00% and 20.00%, depending on climatic conditions and management intensity (Lugato et al., 2014; Jebari et al., 2018).

The SOC stock ratio (the ratio of SOC stock in 2025 to that in 2010) map provided a clear representation of the spatial distribution of soil carbon changes across Hamadan Province (Fig. 5). The map was predominantly characterized by SOC stock ratio values between 0.50 and 1.00, which covered most of the study area and indicated a widespread but moderate decline in SOC stock rather than highly localized degradation. Areas with SOC stock ratios below 0.50, corresponding to reductions exceeding 50.00%, occurred as relatively small and scattered patches distributed across the central, western, and southern parts of the province, rather than forming a continuous zone. These areas likely reflect localized zones of intensive management and soil disturbance that are typically associated with a loss of SOC stock (Chen et al., 2018; Rodríguez Martín et al., 2019). Zones with SOC stock ratios above 1.00, indicating carbon gains, were clearly identifiable, particularly in the northern and southern parts of the province, with some areas exceeding 1.50. These increases may be associated to local environmental conditions (Post and Kwon, 2000). Overall, the spatial pattern indicates that SOC stock declines, with localized areas of severe depletion.

Figure labels and legend: (a) 2010; (b) 2025. SOC stock (Mg C/hm^2): <100.00; 100.00–150.00; 150.00–200.00; 200.00–250.00; >250.00. Scale: 0–20 km.

Fig. 4 Spatial distribution of SOC stock across Hamadan Province in 2010 (a) and 2025 (b)

Figure legend: SOC stock ratio: <0.50; 0.50–1.00; 1.00–1.50; 1.50–2.00. Scale: 0–20 km.

Fig. 5 Spatial distribution of SOC stock ratio (the ratio of SOC stock in 2025 to that in 2010) across Hamadan Province. Values <1.00 indicate SOC stock decline.

Collectively, these results demonstrated that SOC stock decline in Hamadan Province is not only substantial in magnitude but also spatially structured, with the most severe losses occurring in intensively managed irrigated zones. The widespread nature of SOC stock reduction, together with the fragmentation and contraction of high SOC stock areas, reflects a progressive erosion of the soil carbon base under semi-arid conditions. The implications of these findings are significant. Hamadan Province is a key cereal and legume production region in western Iran; the SOC stock degradation has implications that extend beyond local environmental quality to regional food security. At the policy level, national strategies should prioritize SOC conservation, given the widespread deficits documented across Iranian croplands (Mesgaran et al., 2017; Asadi et al., 2025). These findings are consistent with patterns reported for other Mediterranean and semi-arid agroecosystems, where SOC stock depletion is closely linked to long-term agricultural intensification and limited carbon inputs (Lugato et al., 2014; García-González et al., 2018).

4 Conclusions

This study provides clear evidence that SOC depletion has become a dominant and accelerating process in intensively managed semi-arid croplands of Hamadan Province. Over the last 16 a (2010–2025), SOC stock in the 0–30 cm layer decreased from 126.48 to 84.45 Mg C/hm^2, representing a 33.23% reduction in stored carbon. The magnitude of the observed decline in both SOC concentration and stock indicated that current agricultural systems are operating beyond the capacity of these soils to maintain their carbon balance under prevailing climatic conditions.

The spatial analyses revealed that SOC loss is not only widespread but structurally reorganized across the landscape. Former high-carbon areas have fragmented and contracted, while large portions of the province have converged toward low SOC stock states, particularly in intensively managed irrigated plains. The results further suggested that long-term agricultural intensification (characterized by frequent tillage and heavy reliance on mineral fertilizers) has promoted the development of nutrient-rich but carbon-poor soils. While such systems may sustain short-term productivity, they increase the vulnerability of agroecosystems to climate variability and threaten the long-term sustainability of food production in moisture-limited environments. These findings highlight the urgency of integrating SOC conservation into regional agricultural strategies. Without changes in management, including reduced tillage intensity, improved residue management, and greater use of organic amendments, further SOC stock depletion and soil functional decline are expected. Conversely, conservation practices could still preserve remaining SOC reservoirs and slow degradation trajectories.

Overall, this study underscores that sustaining SOC stock is a central challenge for the future of semi-arid agriculture in Iran and similar regions worldwide. The evidence presented provides a scientific basis for prioritizing soil carbon protection as a key component of sustainable land management and climate adaptation policies.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This paper is published as a part of a scientific project supported by the Vice Chancellor for Research and Technology of the University of Zanjan, Iran. The authors are thankful to the University of Zanjan for all supports. The authors also gratefully acknowledged the local farmers and landowners in Hamadan Province, Iran for their support in granting access to agricultural fields and facilitating soil sampling activities. Special thanks are also extended to the technical staff and laboratory personnel for their valuable assistance with soil sample preparation and analysis.

Author contributions

Mehdi NOURZADEH HADAD: conceptualization, investigation, resources, funding acquisition, supervision, and writing - original draft preparation; Jose Antonio RODRIGUEZ MARTIN: conceptualization, investigation, methodology, formal analysis, validation, and writing - review and editing; Akbar HASSANI: investigation, supervision, funding acquisition, data curation, and writing - original draft preparation. All authors approved the manuscript.

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