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Temporal dynamics of soil organic carbon and salinity in irrigated wheat croplands of southwest Iran (2011-2021)

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ABSTRACT

Soil degradation poses a major threat to global food security, particularly in arid and semi-arid regions where intensive agriculture, climate variability, and unsustainable land management practices accelerate the loss of soil health. Among the most pressing challenges are the decline in soil organic carbon (SOC)—a key indicator of soil fertility—and the accumulation of salinity, which together compromise agricultural productivity and ecosystem resilience. This comprehensive study examined decadal changes (2011-2022) in key soil quality indicators across wheat-cultivated lands of Khuzestan Province, Iran's primary wheat belt. Utilizing a systematic sampling approach, we analyzed 254 and 718 representative soil samples respectively collected during 2011 and 2022, assessing electrical conductivity (EC), SOC content through standardized laboratory protocols. Our findings reveal alarming degradation trends: mean SOC levels declined significantly from 0.76 to 0.67% ($p < 0.01$), accompanied by a 13% expansion of carbon-deficient areas (SOC < 1%). Concurrently, salinity levels showed more dramatic increases, with mean EC rising from 4.59 to 7.76 dS m^{-1} ($p < 0.01$), representing a 69% surge in soil salinity and 23% expansion of salt-affected lands (EC > 4 dS m^{-1}). The relationship between SOC and EC exhibited a threshold-dependent pattern: positive correlations ($r = 0.173$ for EC < 4 dS m^{-1}; $r = 0.045$ for 4–8 dS m^{-1}) reversed under higher salinity ($r = -0.122$ for 8–12 dS m^{-1}; $r = -0.148$ for EC > 12 dS m^{-1}). Therfore, The overall weak positive trend between EC and SOC ($r = 0.106$) is likely driven by the predominance of low-salinity samples (76% of the dataset, EC < 8 dS m^{-1}). These trends reflect the cumulative impacts of intensive cropping, inadequate organic amendments, and improper irrigation management over the study period. The documented 11.8% SOC decline and near doubling of salinity levels have substantially degraded the soil resource in this vital food production region, with direct implications for wheat yield potential and long-term agricultural sustainability. Our results underscore the urgent need for adopting threshold-specific management strategies to reverse these damaging trends.

Keywords: Environmental stress, Khuzestan, Soil degradation, Soil health, Sustainable agriculture.

1. Introduction

In Iran, soil salinity is a widespread issue that severely restricts sustainable agricultural production. Large areas of the country's arid and semi-arid regions—particularly the central plateau, southern coastal plains, and the Khuzestan Plain—are affected by varying degrees of salinity (Momeni, 2010). In Iran, approximately 3.7 million hectares of agricultural land are affected by salinity. The presence of saline water and soil in these regions has led to significant challenges in crop growth and productivity. Soil and water salinity significantly impair plant growth, crop productivity, and sustainable agriculture worldwide (Srivastava *et al.*, 2019; Balasubramaniam *et al.*, 2023), affecting approximately 20% of cultivated and 33% of irrigated lands (Machado & Serralheiro, 2017). Excessive salts disrupt cellular osmotic balance, interfere with physiological processes, and reduce water potential in plants (Srivastava *et al.*, 2019). Most vegetables are particularly sensitive to salinity, with low salinity thresholds (Machado & Serralheiro, 2017). In response to this environmental challenge, plants have evolved a complex array of adaptive mechanisms, primarily categorized into three key strategies: (1) osmotic adjustment through compatible solute accumulation, (2) selective ion exclusion at root surfaces, and (3) intracellular ion compartmentalization for tissue tolerance (Shabala & Munns, 2012). These survival mechanisms are mediated through precise regulation of ion homeostasis, particularly Na^+/K^+ ratios, efficient vacuolar compartmentalization of toxic ions, and biosynthesis of osmo-protectants (Ruiz-Lozano et al., 2012). Soil and water salinity reduce crop yield by impairing nutrient uptake in plants. Salinity stress imposes dual constraints on plant systems through both osmotic and ionic mechanisms, significantly compromising agricultural productivity. The primary physiological constraints include: (1) impaired water uptake due to decreased soil water potential, (2) disrupted acquisition of essential macro- and micronutrients, and (3) cytotoxic accumulation of Na^+ and Cl^-. These salinityinduced perturbations manifest morphologically as stunted growth phenotypes, modified root architecture, and biochemical alterations including oxidative damage through elevated reactive oxygen species generation ions (Zörb *et al.*, 2018). Consequently, monitoring soil salinity levels is essential for sustainable land management, as it facilitates the maintenance of optimal nutrient conditions to support plant growth.

Soil organic carbon (SOC) serves as a fundamental determinant of soil health and agricultural productivity. Empirical evidence demonstrates that SOC enrichment in cultivated agricultural systems can substantially elevate grain yields across major cereal crops, with yield responses ranging from 20-70 kg ha^{-1} in wheat, 10-50 kg ha^{-1} in rice, and 30-300 kg ha^{-1} in maize per unit increase (1%) in SOC (Lal, 2006). This productivity enhancement stems from SOC-mediated improvements in critical soil functions, including enhanced moisture retention, regulated soil pH, improved nutrient bioavailability, and stabilization of soil structure (Merino *et al.*, 2004).

Implementation of conservation agriculture principles, including minimized soil disturbance, diversified cropping systems, strategic residue incorporation, and organic inputs, has been shown to effectively promote SOC stabilization (Shibabaw & Alemeyehu, 2015). Beyond its agronomic benefits, SOC accumulation represents a key strategy for climate change mitigation through terrestrial carbon storage while simultaneously enhancing the resilience of agricultural systems (Lal, 2006; Shibabaw & Alemeyehu, 2015). This dual benefit is particularly vital for food-insecure regions, where SOC depletion has contributed to persistent yield plateaus and land degradation (Lal, 2010).

Khuzestan Province accounts for a substantial portion of Iran's wheat production, maintaining approximately 400,000 hectares of irrigated wheat cultivation with mean yields of 4 t ha^{-1} (Ahmadi *et al.*, 2019). Previous studies indicate that most of agricultural soils in the province exhibit significant challenges, including elevated salinity levels, high calcium carbonate content, and nutrient imbalances (Balali *et al.*, 2000). Calcareous soils with low organic matter content, combined with continuous cereal monocropping, significantly reduce the bioavailability of essential trace elements in agricultural systems (Li *et al.*, 2015). Therefore, Khuzestan's unique combination of (1) calcareous parent materials, (2) saline groundwater irrigation, and (3) monoculture intensification drives synergistic SOC-salinity degradation distinct from other arid regions. This study evaluates ten-year temporal variations in soil salinity and organic carbon in wheat-growing regions of Khuzestan Province.

2. Materials and Methods

Khuzestan Province (63,633.6 km²), forming Iran's southwestern border, extends across 29°57'-33°00'N latitude and 47°40'-50°33'E longitude. Khuzestan Plain extends from the southern borders of Andimeshk and Masjed Soleiman to the Persian Gulf and Arvand River. This geomorphological unit spans approximately 300 km north-south and 200 km east-west, encompassing the southern, central, and western regions of the province - areas characterized by hot arid and semi-arid climates. The nearly flat topography (average slope <1%) features salt domes that significantly contribute to land and water salinization. Covering about 65% of the province's total area, this plain dominates Khuzestan's geographical structure. For this study, we collected 254 composite soil samples (0-30 cm depth) from wheat fields across Khuzestan Province (15 counties) during the 2011 growing season (Figure 1). Soil organic carbon (SOC) content was determined using the Walkley-Black wet oxidation method (Walkley & Black, 1934), while electrical conductivity (EC) and pH were measured in the saturated paste extract using an EC meter and pH meter, respectively. A decade later during the 2021-2021 growing season, we collected and analyzed 718 additional soil samples from wheat production regions across Khuzestan Province to assess temporal changes. Statistical processing of the research data was executed in IBM SPSS Statistics v.19.

3. Result and Discussion

Descriptive statistics of soil organic carbon (SOC, %) and salinity (EC, dS m^{-1}) values in wheat-cultivated soils of Khuzestan Province, southwestern Iran, for each study year (2011 and 2021) are presented in Table 1, while frequency distribution plots of the two studied parameters are shown in Figure 2. According to data collected from 2011, soil salinity ranged from 0.5 to 47.2 dS m^{-1} (Table 1), with approximately 63% of the samples below 4 dS m^{-1}, 13% between 4-6 dS m^{-1}, and 24% exceeding 6 dS m^{-1} (Figure 2). The highest salinity level was recorded in Shadegan area (with the average of 12.97 dS m^{-1}), while the lowest was observed in Izeh region (with the average of 0.91 dS m^{-1}). Over the decade-long period, soil salinity across the province ranged from 0.56 to 101 dS m^{-1}, with the mean salinity increasing from 4.59 to 7.67 dS m^{-1} (Table 1). Approximately 40% of the studied soils exhibited salinity below 4 dS m^{-1}, 20% between 4-6 dS m^{-1}, and 40% exceeded 6 dS m^{-1}.

The analytical data reveal significant spatiotemporal variations in soil salinity across Khuzestan province's wheat-cultivated areas. Spatial extremes were observed, with Shadegan exhibiting severe salinity (with the average of 12.97 dS m^{-1}) compared to Izeh's minimal levels (with the average of 0.91 dS m^{-1}). Temporally, the decade-long study period (2011–2021) documented a pronounced increase in mean provincial salinity from 4.59 to 7.67 dS m^{-1}, with values spanning 0.56–101 dS m^{-1} by 2021—indicating both widespread salinization and localized extreme conditions. Frequency distribution analysis showed a bimodal pattern, ie. 40% of soil samples remained below the 4 dS m^{-1} threshold, while another 40% exceeded 6 dS m^{-1} (severely restrictive), suggesting

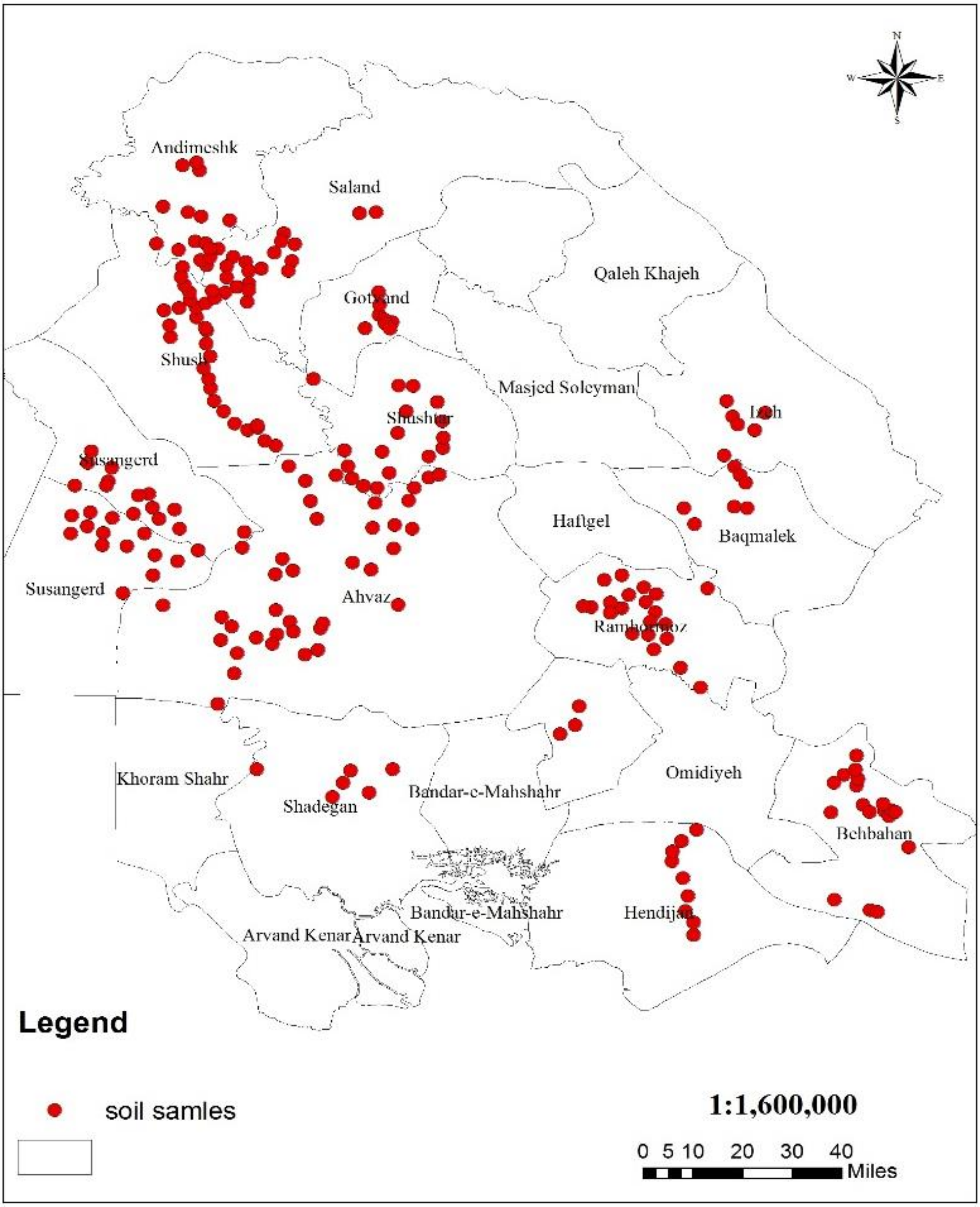

Figure 1. Spatial distribution of soil sampling points in 2011 (Khuzestan Province, southwest of Iran)

Table 1. Descriptive statistics of soil organic carbon (SOC), pH and salinity (EC) in wheat-cultivated soils of Khuzestan Province during 2011 and 2021.

	2011			2021		
	EC (dS m^{-1})	SOC (%)	pH (-)	EC (dS m^{-1})	SOC (%)	pH (-)
Mean	4.59	0.76	7.44	7.67	0.67	7.56
Minimum	0.5	0.03	6.8	0.56	0.03	6.67
Maximum	47.2	1.7	8.4	101.3	1.89	8.35
Std. Deviation	5.95	0.31	0.26	9.78	0.28	0.27

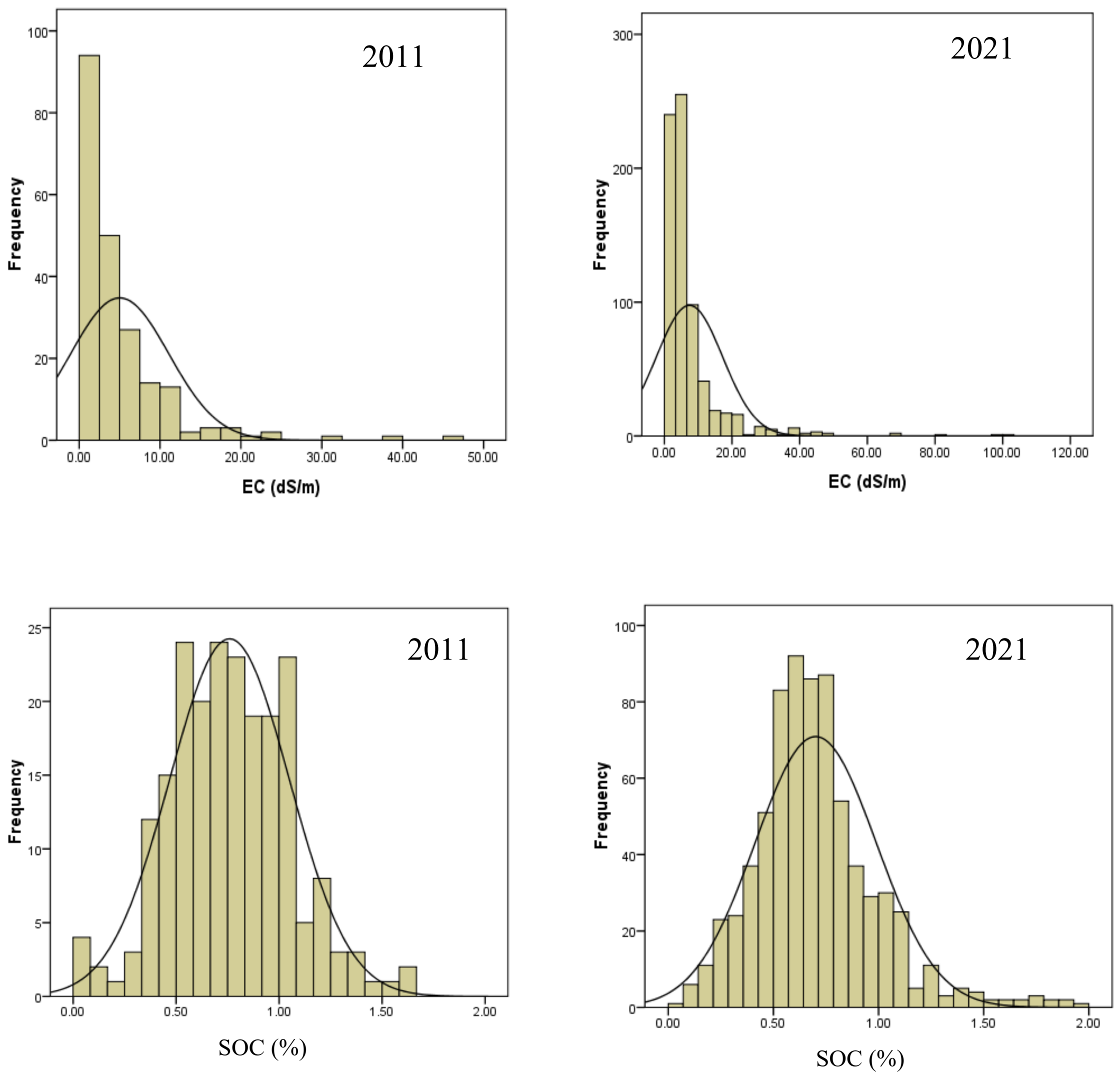

Figure 2. Frequency distribution plots of soil organic carbon (SOC) and salinity (EC) based on agricultural soil samples from wheat-cultivated fields in Khuzestan province during 2011 and 2022.

divergent soil health trajectories. The 67% rise in mean salinity correlates with regional water management practices and climate shifts, warranting targeted remediation in high-salinity zones like Shadegan to safeguard agricultural productivity.

Soil salinization poses a significant environmental threat, reducing agricultural productivity due to unsustainable farming practices and excessive water resource use, particularly in arid regions (Cuevas *et al.*, 2019). Multiple studies highlight the quality of irrigation water as a primary factor inducing soil salinity. Gateazadeh (2023) found that improving irrigation water quality (EC) from 3.61 to 2.01 dS m^{-1} reduced soil salinity in an experimental setting. Similarly, Amini *et al.* (2020) and Rahimi *et al*. (2019) identified saline irrigation water as a major contributor to soil salinity. Jahanbazi *et al*. (2023) noted that reliance on deep groundwater for irrigation, which often has higher salinity due to rock-water interactions, significantly exacerbates soil salinity. Savari *et al*. (2021) also emphasized the role of high-water table levels in increasing soil salinity, particularly in southern and southwestern Khuzestan.

Leaching plays a critical role in managing salinity, as evidenced by the increased salinity observed in abandoned lands where leaching was insufficient (Jahanbazi *et al.*, 2023). According to Cuevas (2019), integrating soil amendments, conditioners, and residue management, alongside tailored irrigation and drainage practices, can substantially reduce soil salinity while boosting crop yields. Additionally, Khuzestan's arid climate—characterized by high temperatures, low precipitation over a 25-year period, and high evaporation rates—accelerates salt accumulation (Amini *et al*., 2020). Land-use changes further compound the issue; converting rangelands to croplands raises irrigation demands, while abandoned fields suffer from inadequate leaching, leading to greater salt buildup. Finally, variations in topography and soil texture influence the spatial distribution of salinity, with fine-textured soils typically retaining more salt than coarse-textured soils (Jahanbazi *et al.*, 2023).

Analysis of 2011 topsoil samples (0-30 cm) revealed organic carbon contents 0.03-1.71 % (with the average of 0.6 %; Table 1). Frequency distribution analysis showed 20% of soils contained less than 0.5 % organic carbon, 30 % between 0.5-0.75 %, 27 % between 0.75-1 %, and 23 % exceeded 1 % organic carbon (Figure 2). The results identified Ahvaz as a SOM-depletion hotspot (0.57±0.19%), contrasting with Izeh's carbon-rich soils (1.06±0.37%). Decadal monitoring (2011-2021) revealed expanding SOM variability (0.03-1.89%), with frequency distribution analysis showing 25% of provincial soils contained <0.5% organic carbon, 45% between 0.5-0.75%, and 20% between 0.75-1% (Figure 2). The analyzed agricultural soils with organic matter content below the 1% threshold fall into the very low fertility category as defined by USDA soil quality standards.

Figure 3 illustrates the extent of soil salinity limitation (EC > 4 dS m^{-1}) and soil organic carbon deficiency (SOC < 1%) and their temporal variations over a ten-year period in wheat-cultivated agricultural lands of Khuzestan province. The decadal analysis (2011-2021) reveals a 23 % increase in salinity-affected wheat areas (37%→60%) and a 13% rise in SOC-deficient soils (77%→90%).

The depletion of SOC in Khuzestan Province's agricultural soils is principally driven by arid climatic conditions. Elevated temperatures coupled with limited precipitation contribute to diminished SOC stocks and prolonged mean residence time (Owji *et al.*, 2024). This pattern reflects national trends, where Rezaei *et al*. (2020) report that 70% of Iran's agricultural topsoil contain < 1% SOC, with merely 4% exceeding 2% SOC in more humid regions. The aridity-SOC relationship is further evidenced by comparative studies showing Mediterranean arable soils maintain lower SOC content relative to their Atlantic counterparts (Romanyà & Rovira, 2011).

Notably, anthropogenic interventions can modulate these patterns. Hajabbasi *et al*. (2010) demonstrate that appropriate irrigation and fertilization regimes may enhance SOC accumulation in arid agroecosystems. Land use practices exert significant influence, with Rezaei *et al.* (2020) documenting higher SOC concentrations in horticultural and irrigated systems compared to rainfed or fallow lands. Long-term agricultural cultivation has been shown to significantly reduce both organic carbon content and aggregate stability in semi-arid soils relative to pasture systems (Safadoust *et al.*, 2016). In contrast, comparative studies demonstrate that organic and integrated management approaches enhance soil organic carbon dynamics in semi-arid regions when compared to conventional agricultural practices (Gorooei *et al*., 2023).

Intensive agricultural practices exert substantial influence on SOC and nitrogen cycling dynamics. Conventional cultivation and tillage operations typically induce SOC depletion, consequently accelerating soil degradation processes (Liu *et al*., 2003, 2006; Kumar *et al.*, 2015). Nevertheless, implementation of optimized management approaches can effectively counteract these negative impacts. Research demonstrates that adopting crop rotation systems, conservation tillage methods, cover cropping, strategic residue retention, and precision fertilization can not only preserve but enhance SOC stocks (Liu *et al.*, 2006). Importantly, sustainable land management practices play a pivotal role in regulating soil carbon and nitrogen fluxes, thereby simultaneously enhancing agricultural productivity and contributing to climate change mitigation efforts (Liu *et al.,* 2003; Purwanto & Alam, 2020).

Soil salinity and SOC in the croplands are closely linked (Zhang *et al*., 2020). The Pearson correlation analysis revealed notable differences in the relationships among soil pH, EC, and SOC between 2011 and 2021 (Table 2). In 2011, the correlations were weak and non-significant, with EC showing a slight positive association with pH ($r = 0.100$) and a negligible negative correlation with SOC ($r = -0.095$), while pH and SOC were almost uncorrelated ($r = 0.010$), suggesting no meaningful associations. In contrast, the 2021 dataset demonstrated significant shifts: EC exhibited a statistically significant negative correlation with pH ($r = -0.168$, $p < 0.01$), indicating that higher salinity levels were associated with lower soil pH. Additionally, SOC showed a significant positive correlation with EC ($r = 0.106$, $p < 0.01$) and a

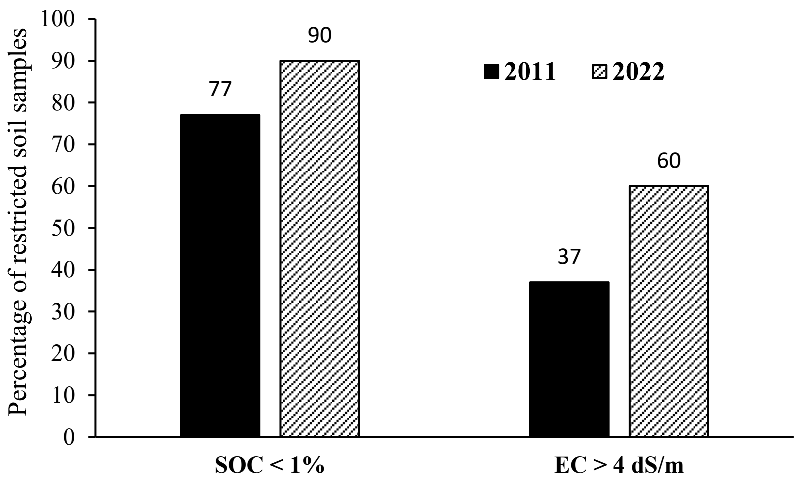

Figure 3. Temporal changes in soil constraints (salinity or electrical conductivity, EC > 4 dS m^{-1} and deficiency of soil organic carbon, SOC < 1%) in wheat-cultivated agricultural soils of Khuzestan province over a ten-year period (2011-2022).

Table 2. Pearson correlation coefficients between pH, electrical conductivity (EC), and soil organic carbon (SOC) in the studied soil samples in 2011 and 2021

	2011			2021		
	EC	pH	SOC	EC	pH	SOC
EC	1			1		
pH	0.100	1		-0.168**	1	
SOC	-0.095	0.010	1	0.106 **	-0.177**	1

** is significant at 1% probability level.

significant negative correlation with pH (r = -0.177, p < 0.01), suggesting that increased organic carbon content was linked to higher salinity but lower pH. However, the practical implications of these weak correlations (all |r| < 0.2) remain uncertain, as large sample sizes can detect even minor effects as statistically significant (Fan *et al.*, 2019). To assess robustness, we conducted additional analyses using random subsets of 30 samples (100 iterations), which confirmed the instability of correlation coefficients (range: -0.32 to +0.49 for EC-SOC). Moreover, a significant direct relationship was observed between the average values of soil EC and SOC in the 15 studied counties (Figure 4), confirming the results reported in Table 2.

In saline and saline–alkaline soils, increased salinity as indicated by higher pH or EC tends to reduce SOC stocks (Zhang *et al*., 2020). Zhang *et al*. (2020) measured SOC stock in the range 2.3 and 11.7 kg C m^{-2} and reported that the highest pH values (8.6–9.0) coincided with the lowest SOC. Similarly, Su *et al*. (2018) documented significant decreases in SOC, microbial biomass carbon, and easily oxidizable carbon along a gradient of increasing EC. Prior studies (e.g., Zhang *et al.*, 2020; Su *et al.*, 2018) reported stronger inverse relationships between EC and SOC in saline soils, whereas our results showed a context-dependent pattern (Table 3): a positive trend in low-salinity soils (EC < 8 dS m^{-1}; r = 0.045–0.173) but a negative trend in high-salinity soils (EC > 8 dS m^{-1}; r = -0.122 to -0.148). This discrepancy may arise from the dominance of low-salinity samples (76% of the dataset), highlighting the need for stratified analyses by salinity levels. Notably, the number of soil samples in the lower salinity categories (548 samples combined) was substantially higher than in the high-salinity groups (170 samples combined). Importantly, while microbial processes (Dong *et al.*, 2022) and EC thresholds (Jia *et al.*, 2023) theoretically support salinity-driven SOC reduction, our observational data suggest that this relationship may be nonlinear and scale-dependent. Future work should combine controlled experiments with larger spatial sampling to disentangle these effects.

4. Conclusions

The findings of this study highlight a concerning decline in soil health across Khuzestan's wheat-growing regions, marked by significant increases in soil salinity (69%) and reductions in organic carbon (11.8%) over the past decade. These trends threaten the long-term sustainability of

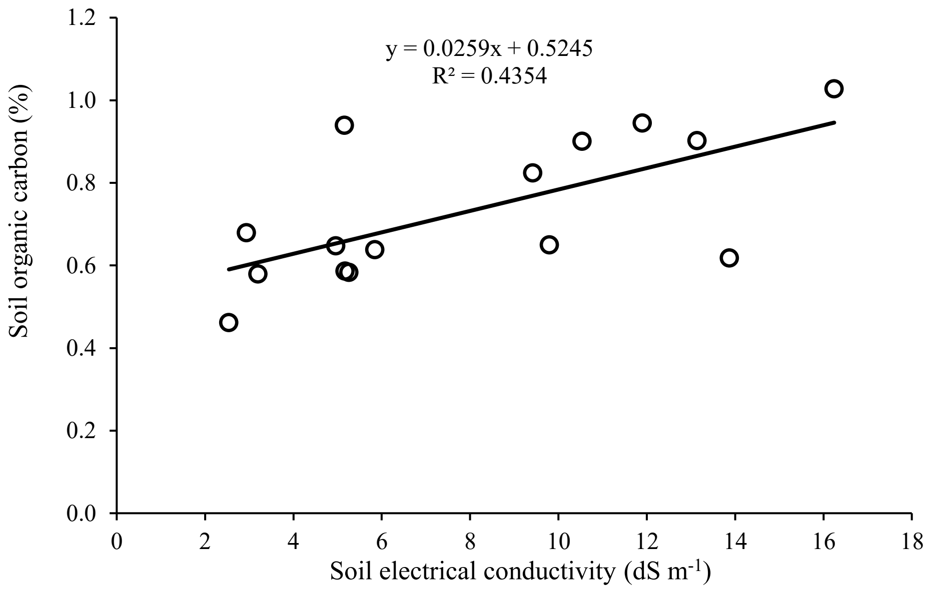

Figure 4. The linear relation between average values of soil organic carbon content vs. electrical conductivity in 15 counties of Khuzestan Province (2021)

Table 3. The relationship between soil electrical conductivity (EC) and organic carbon content (SOC) across different salinity levels - as classified from 2021 soil samples

Soil salinity level	Linear relationship	r	Number of soil samples
EC < 4 dS m^{-1}	SOC= 0.0507EC +0.522	0.173	298
4 dS m^{-1} < EC < 8 dS m^{-1}	SOC= 0.0901EC +0.643	0.045	250
8 dS m^{-1} < EC < 12 dS m^{-1}	SOC= -0.0306EC +1.0637	-0.122	71
12 dS m^{-1} < EC	SOC= -0.0028EC +0.8887	-0.148	99

agricultural production in one of Iran's most vital breadbaskets. The expansion of carbon-deficient and salt-affected soils underscores the consequences of current intensive farming practices, including inadequate organic matter recycling and improper irrigation management. Our analysis of SOC-salinity relationships revealed a critical threshold effect: while low salinity levels (EC < 8 dS m^{-1}) showed a weakly positive association with SOC, higher salinity regimes exhibited negatively significant correlations, emphasizing the need for differentiated remediation approaches. Therefore, our observational data suggest that the EC - SOC relationship may be nonlinear and scale-dependent. To reverse this degradation, immediate implementation of regenerative practices (such as conservation tillage, crop residue retention, organic amendments, and precision irrigation) is critical. Furthermore, policy interventions should promote soil health monitoring and farmer education programs to encourage sustainable land management. Priority should be given to hotspot regions where synergistic SOC-salinity degradation is most acute. Addressing these soil constraints is essential not only for safeguarding wheat productivity but also for enhancing climate resilience in Iran's agricultural systems. Future research should evaluate the effectiveness of different remediation strategies under local conditions to develop tailored solutions for this pressing challenge.

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