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BRACKISH WATER IRRIGATION ALTERS SOIL ORGANIC AND INORGANIC CARBON PARTITIONING AND DEGRADES ECOSYSTEM FUNCTION IN AN ARID ALKALINE GRASSLAND

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Abstract

Brackish water irrigation is increasingly adopted in arid regions, yet its volume-dependent effects on soil carbon partitioning and ecosystem integrity remain unclear. In this study, we aimed to investigate the effects of brackish water irrigation (EC = 5.76 dS m^{-1}) on soil salinization and grassland productivity in a semi-arid saline-alkali ecosystem in Xinjiang, China. We determined an optimal irrigation volume, among 15 (C1), 30 (C2), and 45 (C3) L m^{-2} $year^{-1}$, that balances biomass production against the risk of salt accumulation, thereby identifying a sustainable water management strategy for the region. The results showed that all irrigation treatments significantly increased total soil carbon compared to the rainfed control. However, organic and inorganic carbon pools exhibited sharply divergent responses to application rate. Moderate irrigation maximized soil organic carbon (SOC) accumulation in subsurface horizons (39-51% above control) and sustained a balanced SOC:SIC ratio (0.92). High-volume irrigation crossed a critical ecological threshold: species richness declined by 83%, aboveground biomass by 44%, and surface SOC decreased, while pedogenic carbonate accumulation drove the SOC:SIC ratio to 0.34 indicating strong inorganic carbon dominance. Furthermore, the irrigation volume governed soil inorganic carbon (SIC) dynamics, whereas vegetation covers controlled SOC patterns. The SOC:SIC ratio correlated positively with microbial biomass carbon ($r = 0.78$, $p<0.001$) and negatively with bulk density ($r = -0.65$, $p<0.001$), confirming that inorganic carbon dominance coincides with biological and structural degradation. These findings confirm that low-volume brackish water irrigation (≤30 L m^{-2}) offers a viable strategy for rehabilitating degraded saline-alkali grasslands, whereas higher volumes risk promoting inorganic carbon accumulation at the expense of soil biological and structural integrity.

Key words: Brackish water irrigation; SOC: SIC ratio; Saline-alkali ecosystem; Grassland degradation; Microbial biomass carbon

Introduction

Grasslands can mitigate climate change through the storage of carbon dioxide in organic and inorganic soil pools (Amundson *et al*., 2019; Lal, 2020). However, water scarcity severely constrains these ecosystems, particularly in arid and semi-arid regions, prompting exploration of alternative irrigation sources (Liu *et al*., 2020; Falkenmark *et al*., 2022). Brackish water irrigation is increasingly common and critically important in many water-stressed arid and semi-arid areas worldwide, including parts of Central Asia, the Middle East, North Africa, and northwestern China (e.g., Xinjiang), where freshwater resources are depleting due to population growth, agricultural expansion, and climate change impacts such as reduced precipitation, higher evapotranspiration, and more frequent droughts (Anon., 2021).

Globally, brackish groundwater and marginal-quality water are already used for irrigation in regions facing severe freshwater shortages, with estimates indicating that non-conventional sources like brackish water could supplement up to 20-30% of irrigation needs in some arid zones to maintain productivity amid declining freshwater availability [e.g., studies in Xinjiang and similar environments (2024-2025). Owing to its salinity content, brackish water is both threatening and promising. Its use could support vegetation persistence or growth in dry regions; however, it also introduces salts and alters soil physicochemical properties, restricting plant growth and modifying biogeochemical cycles (Rengasamy *et al*., 2016; Gupta *et al*., 2020). Salinity affects negatively by causing osmatic stress and ion toxicity, which reduces germination, growth, and productivity, ultimately decreasing aboveground biomass and carbon inputs into the soil (Munns and Tester, 2008; Deinlein *et al*., 2014). Global estimates suggest that soil carbon stocks vary considerably across ecosystem types and land-use histories (Batjes, 2014). The reduction in soil organic carbon is primarily associated with the decline in primary production, which in turn leads to a reduction in soil organic matter (Schmidt *et al*., 2011; Luo *et al*., 2017).

Brackish water irrigation that is abundant in both calcium (Ca^{2+}) and bicarbonate (HCO_3^-) minerals has been reported to enhance precipitation of pedogenic carbonates, and therefore enlarge the pool of soil inorganic carbon (Sherrod *et al*., 2002; Zamanian *et al.,* 2021). As an ecosystem shifts from organic to inorganic carbon storage, the capacity for carbon sequestration and ecosystem stability can change substantially

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(Lehmann & Kleber, 2015; Bradford *et al*., 2019). The changes in the pH, EC, and bulk density of soil due to salinity may create complex feedback mechanisms. Sodium (Na^+) and calcium (Ca^{2+}) can disrupt soil structure and stabilize it, respectively, and allow calcium and calcium carbonate to increase aggregation and SOC retention, respectively (Rengasamy *et al*., 2016; Hillel, 2020).

Salinity has been reported to retard microbial activity and slow the mineralization of SOC, such that net SOC accumulation is expected to persist despite smaller carbon inputs (Yan *et al*., 2015; Trivedi *et al*., 2016; Chen *et al*., 2022). These changes are depth-dependent but their distribution is poorly understood, which is essential for estimating the resilience and stability of the soil carbon sink in the long term (Jackson & Jobbágy, 2000; Wang *et al*., 2021). In the case of degraded grasslands, such as saline-alkali ecosystems of Central Asia, which are highly sensitive to human disruption, a knowledge of these linkages is vital (Várallyay, 2010; Qadir *et al*., 2021). Drought species (*Suaeda salsa*) and soil are adapted to stress, which leads to alkalinized and carbon-depleted soils, and land-use changes in grassland ecosystems have been shown to significantly influence soil microbial community structure (Deng *et al*., 2017). Brackish water is expected to regulate carbon via geochemistry and has the potential to drive such ecosystems past a critical biological boundary. The ongoing global decline in biodiversity and ecosystem services has been extensively documented across terrestrial ecosystems (Anon., 2019). There is no systematic research that has examined the trade-offs of vegetation health, soil behavior and organic inorganic carbon partitioning in saline alkalinity grasslands under controlled gradients of brackish irrigation. This gap limits ability to predict the long-term effects of brackish water irrigation on numerous ecosystem services including climate regulation, biodiversity preservation, and soil stability (Graf *et al*., 2019; Bardgett *et al*., 2021).

The primary objective of this study was, therefore, to systematically investigate the effects of brackish water irrigation on key soil properties, including pH, bulk density, electrical conductivity, and the concentrations of eight major ions (Ca^{2+}, Mg^{2+}, K^+, Na^+, CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}), within the grassland ecosystem of Xinjiang, China. Additionally, the study aimed to examine the vertical distribution patterns of soil organic carbon (SOC) and soil inorganic carbon (SIC) in response to varying irrigation volumes. These findings are expected to inform the development of sustainable irrigation strategies that balance water resource utilization with soil health preservation in arid regions. Future research should focus on long-term monitoring of carbon dynamics under brackish irrigation, integration of hydro-chemical modeling to predict ion accumulation, and the design of region-specific management practices to mitigate salinization risks while maintaining grassland productivity and ecosystem stability.

Materials and Methods

Study site and experimental design: The study was carried out at two consecutive annually growing seasons (2024 and 2025) of saline alkali grassland of HuYangHe, Xinjiang, China. The region experiences a usual arid continental climate, which is characterized by an average precipitation of under 150mm and a potential evaporation rate of 2000mm per annum. Native plants mostly include halophytes and several species of grasses such as *Suaeda salsa*, *Kalidium foliatum*, *Leymus chinensis*, *Puccinellia tenuiflora*, and *Achnatherum splendens*, which have adapted to occur in specific soils that are salty and soda soils. The characteristics of the brackish irrigation water were ascertained as follows: pH = 7.4, EC = 5.76 dSm^{-1}, NH_4^+-N = 1.18 mgL^{-1}, NO_3^--N = 0.26 mgL^{-1}, PO_4^{3-}-P = 0.016 mgL^{-1}, total phosphorus = 0.02 mgL^{-1}, BOD = 4.30 mgL^{-1}, COD = 70.56 mgL^{-1}, and suspended particles = 4.21 mgL^{-1}. Concentrations of heavy metals were minimal or undetectable (Pb = 0.03 mgL^{-1}; As, Cd not found).

The experimental design was a randomized complete block design with 4 irrigation levels conducted on 10 m × 10 m plots (n=4 replicates/blocks per treatment). These treatments included a rainfed control (CK) and three brackish water irrigation regimes with the same water quality but varying annual application volumes: low-volume (C1) at 15 L m^{-2} $year^{-1}$, medium-volume (C2) at 30 L m^{-2} $year^{-1}$, and high-volume (C3) at 45 L m^{-2} $year^{-1}$. Each treatment was replicated 4 times (four independent blocks), with each block containing one plot of each treatment level to account for spatial variability in the saline-alkali grassland. Irrigation was applied monthly during the growing season (May–September) in both years (2024 and 2025), with monthly applications of 5, 10, and 15 L m^{-2} for C1, C2, and C3, respectively, resulting in seasonal totals equivalent to 0 mm (CK), 15 mm (C1), 30 mm (C2), and 45 mm (C3) annually.

These additional supplies of irrigation, though relatively small compared to annual evaporation rates much higher than 2000 mm, were during the most active period of growing, and were sufficient to cause substantial changes in this arid ecosystem that depends on water, as it was shown by the recorded changes of vegetation biomass, cover and soil properties during the two years.

The experimental design therefore represents reality of limitation of water quality in the real world with management being meant to maximize application volume. The Walkley-Black wet oxidation method was used to determine soil organic carbon (SOC) (Walkley & Black, 1934). Soil inorganic carbon (SIC) was measured through modified pressure-calcimeter (Sherrod *et al*., 2002).

Vegetation sampling and biomass quantification: Stratified sampling was used to measure vegetation parameters in order to measure structural and functional responses. A 10 mx 10 m quadrat was then set up in every treatment plot to observe the shrub vegetation with all individuals recognized to species level and their height and cross-sectional width of the crown recorded. Sebaceous vegetation was randomly allocated in three 1 m^2 sub-quadrats in each of the main plots creating a total of 12 sub-quarters per treatment. Using validated taxonomic keys and plant recognition software (Hua Cao Jun v3.2, Beijing Plant Identifier Inc.), all the vascular plants species in each sub-quadrat were identified, and the percent cover was estimated visually using a modified Braun-Blanquet scale.

All vegetation was cut on top of the soil at the ground level within each 1m x 1m sub-quadrat to get aboveground biomass. The samples were put in specific paper bags and delivered to the laboratory within four hours after collection. Upon arrival, the fresh weight of each sample was immediately determined gravimetrically followed by the oven-drying of the fresh weight at 105°C during 30 min to stop the activity of any enzyme and followed by drying of the fresh weight at 85°C until a steady weight was attained, usually between 48 h and 72 h. Bio-diversity was measured i.e. the number of species per square meter and plant cover was measured as the percentage of the ground covered by the vegetation.

Soil sampling and analytical procedures: The soil samples were picked at 7 depths at 0-10, 10-20, 20-30, 30-40, 40-60, 60-80, 80-100 cm at the conclusion of each growth period using a stainless-steel auger with a diameter of 5 cm. Three copies cores were acquired and pooled both with respect to treatment and depth. Physicochemical analysis of the samples was done by air-drying, passing through a 2-mm screen and thoroughly pulverizing.

The Walkley-Black wet oxidation method was used to determine SOC (Isbell *et al*., 2022). 10 mL of 1N potassium dichromate ($K_2Cr_2O_7$) and 20 mL of concentrated sulfuric acid (H_2SO_4) were digested with 1.0 g of finely pulverized soil (<0.15 mm) at 125°C for 30 min. The left-over dichromate was titrated in 0.5N ferrous ammonium sulfate taking ferroin as the indicator. The quantification of SIC involved the use of the calcimetric method (Bardgett *et al*., 2014). The reaction of soil (approximately 5.0 g) with 10% HCl in a closed system was followed and the CO_2 was determined using a volumetric method. The pH of soil and electric conductivity (EC) of the soil samples were measured on 1:5 soil-to-water solution with calibrated digital meters (pH: Orion Star A211; EC: Hanna HI2300). The separation of water-soluble cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) and anions (CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2}) was accomplished by means of deionized water at 1:5 ratio and the ion chromatography (Dionex ICS-5000+) was used in line with the standard procedures (Anon., 2017).

Statistical analysis

All the statistical analyzes have been conducted with the help of R version 4.3.0 (R Core Team, 2023). Linear mixed-effects models were used to compare treatment effects on the vegetation characteristics (cover, richness, biomass), and soil characteristics (SOC, SIC, pH, and EC) as fixed variables and plot as random variables. The model's general form was:

$$Y_{ijkl} = \mu + T_i + D_j + S_k + (T \times D)_{ij} + (T \times S)_{ik} + (D \times S)_{jk} + (T \times S \times D)_{ijk} + \varepsilon_{ijkl}$$

Where Y_{ijkl} is the variable of response, μ is the overall mean, T_i is the influence of the i-th treatment, D_j is the j-th depth, S_k is the k-th season, and ε_{ijkl} represents are residual error. Several of the simplification steps were the result of the complexity of the full three-way interaction model with limited replication, which we employed by degrees of simplification. Higher order interactions that were non-significant ($p \geq 0.05$) were removed systematically meaning that only significant terms were included in the final model. The Shapiro-Wilk and the Levene tests were used to validate the assumption of normality and homoscedasticity, respectively. To evaluate the assumptions of normality and homoscedasticity Shapiro-Wilk and Levene tests were used respectively. Post-hoc comparisons were conducted based on the results of using the Tukey HSD test on the detection of significant main effects ($p<0.05$). All values are represented in mean and standard error (SE). The ggplot2 tool was used to create graphical results (Wickham, 2016).

As a result of this purposely designed correlation of irrigated volume and irrigation volume between the experimental design and the real-world situation of agrarian constraint, we conducted further covariate analyses with the purpose of isolating treatment effects based on salinity-specific availability and water availability. The analyses showed used water volume and electrical conductivity as continuous predictors in the mixed-effects models to determine that each response variable was affected by them.

Results

pH and EC dynamics: To evaluate the effects of brackish water irrigation on soil chemical environment, we first analyzed the dynamics of soil pH and electrical conductivity (EC) across different irrigation volumes, growing seasons, and sampling depths. The results showed significant responses of soil pH to brackish irrigation (Fig. 1). The control plots showed strongly alkaline surface conditions (pH 8.24-9.01). Systematic irrigation using brackish water decreased the pH of the soil in a volume-related fashion though not in strictly linear way. The treatment with high volume (C3) decreased the surface soil pH to 8.00-8.64 which means that there was a major shift towards less alkalinity (more neutral) conditions. Responses of intermediate were proportional: C2 reached the pH of 8.11-8.28 (in most cases the lowest) and C1 reached the pH of 8.15-8.47. The seasonal patterns showed greater stability of the pH in the brackish water treatments during the farming period, but control plots showed a lot of variation especially after precipitation events temporarily raised pH owing to the concentration of bases. Furthermore, strong negative relationship between soil pH and electrical conductivity (EC) ($r = -0.37$, $p<0.001$) was observed (Fig. 1), which implied that as EC of soil increased, caused by salt deposition, the pH of the soil would consequently be diminished. Moreover, the plot analysis of soil depth profiles showed that there was a consistent reduction in the pH with the increasing depth in all the treatments, and the vertical gradient (high pH at the surface) was also the largest in the CK plots.

The larger the volume of irrigation the more EC was observed to rise in the soil ($p<0.001$). The EC of the control soils was low with a range of 0.17 to 0.47 dSm^{-1}. There were increment steps in the brackish irrigation treatments: C1 reached 0.35-1.83 dSm^{-1}, C2 attained 1.15-1.94 dSm^{-1}, and C3 approached 1.69-3.21 dSm^{-1}. Despite the high EC of the irrigation water (5.76 dSm^{-1}) the EC values in the soil were moderate, which was likely caused by the salt leach somewhere beyond the sampled profile (0-100 cm), the absorption of ions by plants and the effect of dilution in the soil structure, a characteristic feature of well-drained arid soils under intermittent irrigation. The same statistically significant EC hierarchy (C3 > C2 > C1 > CK) was observed throughout the sample dates and depths in the soil with maximum values of electrical conductivity mentioned in mid-season (July) with the effects of evapo-concentration.

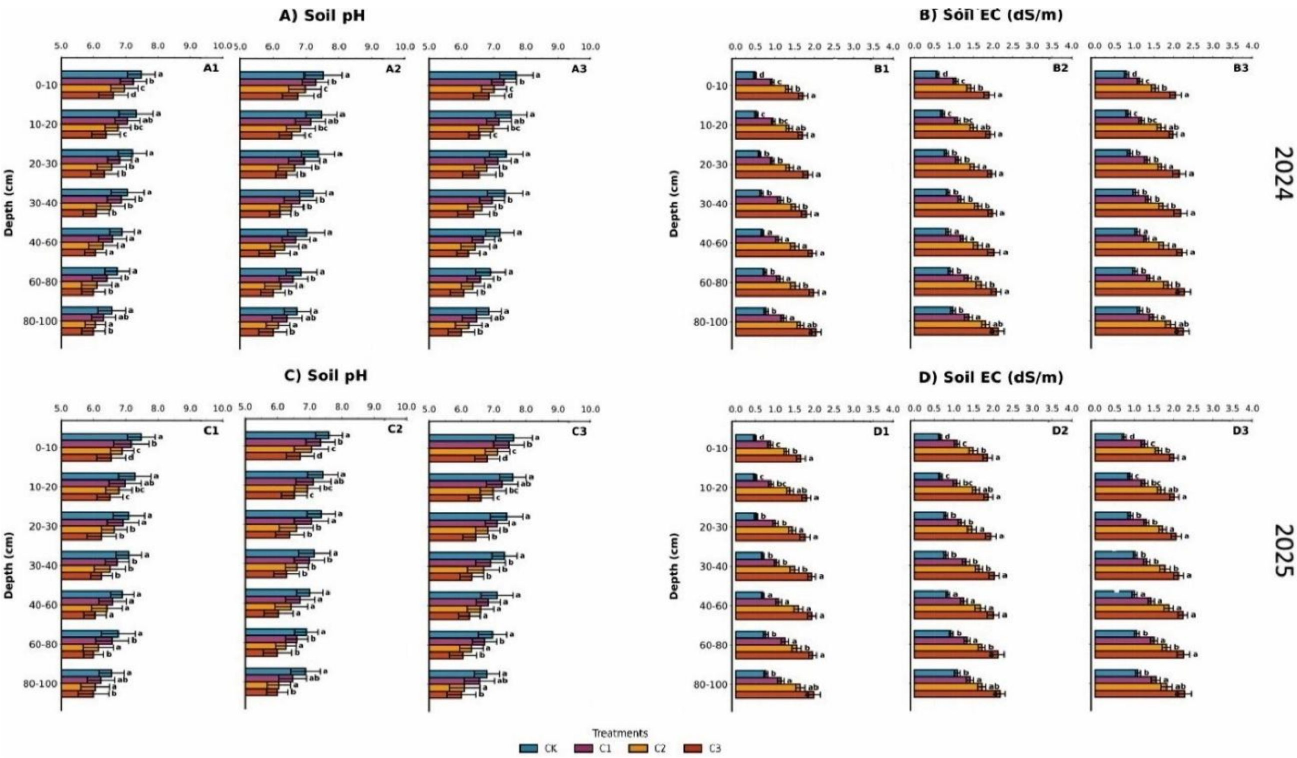

Fig. 1. Soil pH and electrical conductivity (EC) dynamics across brackish water irrigation treatments, depths, and seasons of 2 years (2024-2025). Where A1, A2, A3, represent three seasons of soil pH in year 2024; B1, B2, B3, represent three seasons of soil EC in year 2024; C1, C2, C3, represent three seasons of soil pH in year 2025; and D1, D2, D3, represent three seasons of soil EC in year 2025. CK = rainfed control; C1 = 15 Lm^{-2} year^{-1}; C1 = 30 Lm^{-2} year^{-1}; C3 = 45 Lm^{-2} year^{-1}. S1, S2, S3 = early, mid, and late growing season, respectively.

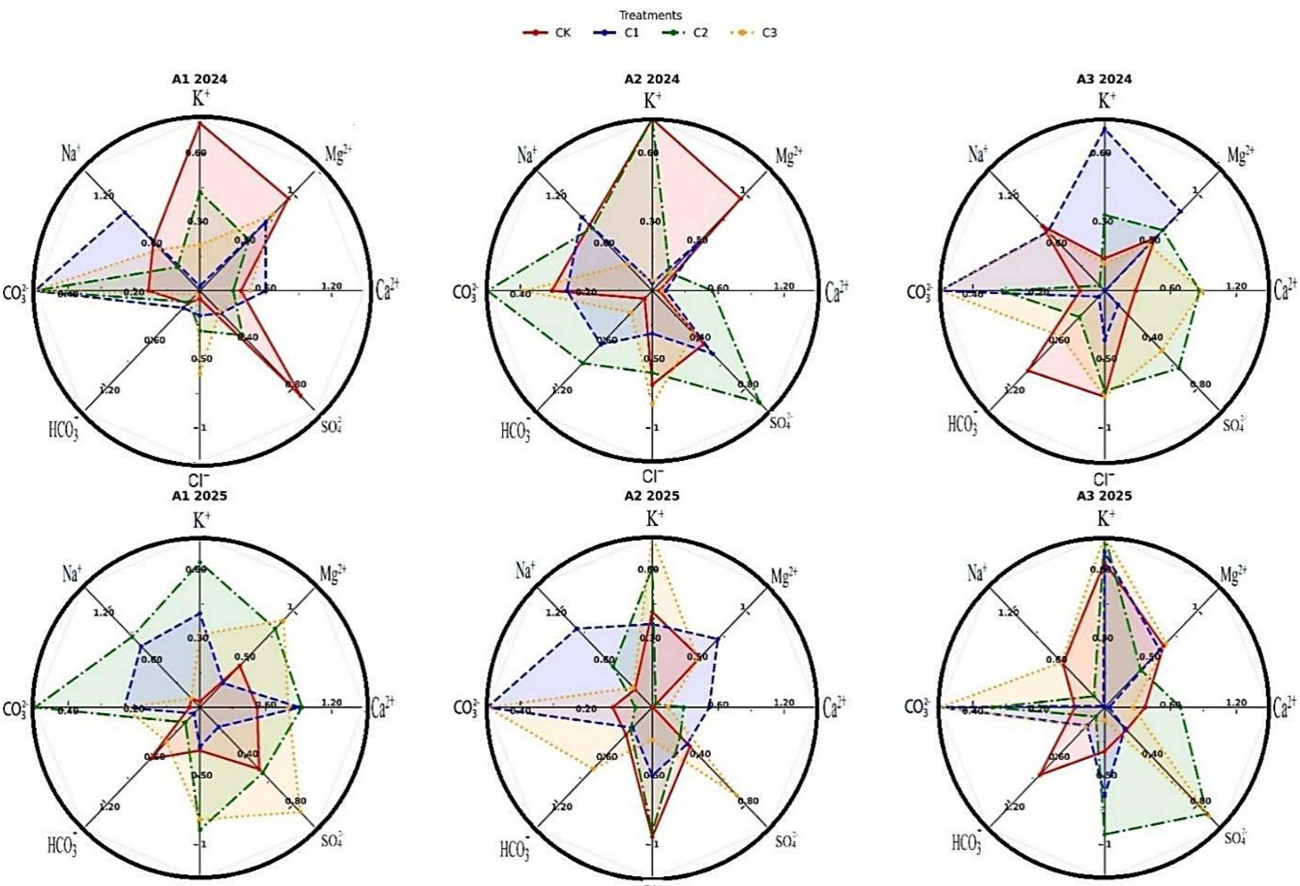

Fig. 2. Changes in Sodium Adsorption Ratio (SAR) across irrigation treatments indicating increasing sodicity risk (2024-2025). Ions concentrations are expressed in g kg^{-1}. CK = rainfed control; C1 = 15 Lm^{-2} year^{-1}; C1 = 30 Lm^{-2} year^{-1}; C3 = 45 Lm^{-2} year^{-1}. Error bars represent standard error (n = 4). SAR threshold values of 3 and 13 are indicated for reference.

Table 1. Seasonal vegetation, biomass, species richness dynamics across brackish irrigation (2024-25). Values are mean ± SE (n=4).

Year	Season	Treatment	Vegetation cover (%)	Species richness (no./m²)	Biomass (g/m²)	Dominant species*
2024	S1	CK	19.9 ± 1.1	4.3 ± 0.4	78.3 ± 7.8	K.F, A.S, S.S
		C1	53.9 ± 5.9	3.0 ± 0.3	122.5 ± 12.3	K.F, A.S, L.C
		C2	92.4 ± 4.2	4.7 ± 0.5	278.9 ± 27.9	S.S, L.C, P.T
		C3	97.2 ± 29.9	3.0 ± 0.3	245.7 ± 24.6	S.S, P.T, L.C
	S2	CK	15.4 ± 1.7	4.3 ± 0.4	68.3 ± 6.8	K.F, A.S, S.S
		C1	38.9 ± 4.3	4.0 ± 0.4	103.5 ± 10.4	L.C, K.F, A.S
		C2	82.0 ± 9.0	5.0 ± 0.5	201.3 ± 20.1	S.S, L.C, P.T
		C3	89.3 ± 4.1	3.3 ± 0.3	332.5 ± 33.3	S.S, P.T
	S3	CK	15.0 ± 0.6	5.0 ± 0.5	72.0 ± 7.2	K.F, A.S, S.S
		C1	19.5 ± 2.1	4.0 ± 0.4	100.0 ± 10.0	L.C, K.F
		C2	73.1 ± 8.0	4.7 ± 0.5	254.6 ± 25.5	L.C, S.S, P.T
		C3	86.3 ± 3.7	4.0 ± 0.4	337.8 ± 33.8	S.S
2025	S1	CK	15.1 ± 1.7	4.0 ± 0.4	72.0 ± 7.2	K.F, A.S, S.S
		C1	8.5 ± 0.9	3.0 ± 0.3	87.3 ± 8.7	K.F, A.S
		C2	21.4 ± 2.4	3.0 ± 0.3	152.2 ± 15.2	L.C, K.F
		C3	53.9 ± 5.9	2.0 ± 0.2	190.4 ± 19.0	S.S, L.C
	S2	CK	13.5 ± 1.5	4.0 ± 0.4	68.8 ± 6.9	K.F, A.S, S.S
		C1	6.8 ± 0.7	2.0 ± 0.2	72.4 ± 7.2	K.F, A.S
		C2	17.6 ± 1.9	3.0 ± 0.3	140.7 ± 14.1	L.C
		C3	43.8 ± 4.8	2.3 ± 0.2	212.8 ± 21.3	S.S
	S3	CK	5.0 ± 0.6	5.0 ± 0.5	65.4 ± 6.5	K.F, A.S, S.S
		C1	6.1 ± 0.7	1.0 ± 0.1	68.4 ± 6.8	K.F
		C2	13.6 ± 1.5	2.0 ± 0.2	122.4 ± 12.2	L.C
		C3	29.4 ± 3.2	2.0 ± 0.2	164.7 ± 16.5	S.S

Species abbreviations: S.S = *Suaeda salsa*, K.F = *Kalidium foliatum*, L.C = *Leymus chinensis*, P.T = *Puccinellia tenuiflora*, A.S = *Achnatherum splendens*

The analysis of the solubility soil ion content revealed that there were considerable changes in the soil chemistry as determined by the quality of irrigation water. Sodium concentration increased almost 90-fold; the concentration rose from 12.40 ± 1.20 mg kg^{-1} in CK to 1124.8 ± 45.6 mg kg^{-1} in C3. There was also parallel increase observed in chloride that increased 67-folds initially from 23.4 ± 2.1 mg kg^{-1} to 1567.8 ± 48.9 mg kg^{-1}. The situation with calcium was more complex; even though its absolute concentration was increased after 156.3 ± 1.7 mg kg^{-1} in C1, up to 489.2 ± 18.9 mg kg^{-1} in C3, its relative proportion in the cation exchange complex was decreased with the maximum volume of water added as Na^+ predominantly accumulated.

Sodium adsorption ratio and sodicity risk: Sodium Adsorption Ratio (SAR), which is a very crucial indicator of risk of sodicity in soils, increased significantly and steadily through the irrigation regimes (Fig. 2). The control treatment (CK) had a low risk of SAR of 0.46 ± 0.03. The C1 treatment (low to moderate risk) and C2 (moderate risk) treatment resulted in a significant increase to 1.95 ± 0.51 and 2.45 ± 0.17, respectively, and a maximum of 4.13 ± 2.04 with C3 treatment (moderate to high risk in sensitive soils). According to the international standards such as those issued by USDA, values above 13 usually typify sodic soils but above 3 can begin to alter soil structure in some sensitive alkaline grasslands such as those that were investigated in this particular study. The statistical analysis showed that there was significant positive correlation between SAR and soil EC ($r = 0.61$, $p<0.001$) and significant negative relationships between SAR and soil hydraulic conductivity ($r = 0.58$, $p<0.001$). A shift between Ca^{2+} exchange complex into Na^+ exchange complex particularly with the C3 treatment implies that there were major and negative changes in the structural stability of the soil and highlights the impact of increased sodicity on the physical health of the soil in this ecosystem.

Vegetation responses to brackish irrigation: Irrigation of brackish water caused a major alteration in the structure of plant communities in an apparent volume-dependent manner (Fig. 2, Table 1). The control plots had a mean species richness of 12.3 ± 1.2 species m^{-2} of species all over the two years of study. Diversity reduced drastically between brackish and irrigation conditions: C1 maintained 8.4 ± 0.8 species m^{-2} (-32%), C2 maintained 5.2 ± 0.6 species m^{-2} (–58%), and C3 maintained 2.1 ± 0.4 species m^{-2} (-83%). The regression analysis revealed that there was a very significant negative relationship between the amount of irrigation and the species richness at the plot level ($r = -0.89$, $p<0.001$).

The level of irrigation had a large parabolic effect on aboveground biomass (Fig. 3). The average biomass of the two plots in the control (CK) was 134.2 ± 12.3 gm^{-2}. The biomass was maximized in case of low-volume irrigation (C1: 187.6 ± 15.4 gm^{-2}, +40%), was highest in moderate-volume irrigation (C2: 312.8 ± 21.6 gm^{-2}, +133%), and least in high-volume irrigation (C3: 75.4 ± 8.9 gm^{-2}, -44%). Table 1 gives detailed biomass per season. This tendency creates a significant ecological boundary at about 30 Lm^{-2} year^{-1}, which is followed by a reversed growth in the early productivity with the emergence of systemic decay. Cover vegetation had a close relationship with above ground biomass parabolic trajectory. Mean percent vegetation cover was 45.2 ± 3.5% in CK, which increased to 62.8 ± 4.2% in C1 and maximum vegetation cover was 85.4 ± 5.1% under the C2 treatment. Coverage under the high stress C3 state was reduced to 25.3 ± 2.8%. This change in coverage was also accompanied by a great restructuring of plant community. As CK (12 species, Shannon diversity index H′ = 2.45) was sequentially simplified, leaving only *Suaeda salsa* as a near-monoculture in C3 (2 species, H′ = 0.68). Taxonomic diversity was moderately maintained (5 species, H′ = 1.82) in the C2 treatment though there was considerable skew heterogeneity with only three salt-tolerant species constituting nearly 85% of the total vegetative cover.

Soil organic carbon content: Treatments seemed to display significant differences in soil organic carbon (SOC) that exhibited both vertical and temporal patterns (Fig. 3). Under the rainfed control (CK) plots, the average SOC content at the 0-30 cm was found to be 9.3 ± 12 g kg^{-1} and 40-100 cm was found to be 6.8 ± 0.9 g kg^{-1} across the two-year period. The highest levels of SOC was also achieved with moderate levels of irrigation (C2, 30 Lm^{-2} year^{-1}) with the average being 14.1 ± 0.8 g kg^{-1} (~51% higher than CK) in the 030 cm layer and 9.4 ± 0.7 g kg^{-1} (~39% higher than CK) in the 40-60 cm layer. As compared to the control, this treatment resulted in a rather homogeneous soil organic carbon profile with depth. Compared with low-volume irrigation (C1), high-volume irrigation (C3) resulted in moderate surface SOC levels (10.0–10.8 g kg^{-1}) prior to the first year. However, C3 also led to time-dependent reductions in surface SOC across most layers, with changes ranging from negative to positive values (e.g., −0.76 g kg^{-1} from the initial to the second year, and −0.02 g kg^{-1} relative to control), likely due to limited organic matter inputs and/or stress responses such as increased salinity.

Soil inorganic carbon content: The amount of soil inorganic carbon (SIC) on average grew with the amount of irrigation applied in both surface and near-surface layers (Fig. 3). The control treatment showed high and constant SIC concentrations of 13.0 ± 0.5 g kg^{-1} and 11.4 ± 0.6 g kg^{-1} in the 0-30 cm and 40-100 cm layers respectively in both years. The greatest amount of accumulation of SIC occurred with high-volume irrigation (C3, 45 Lm^{-2} year^{-1}), with means of 22.1 ± 2.8 g kg^{-1} in the 030 cm layer (to 26.5 g kg^{-1} in the 0-10 cm layer in year 2), which corresponded to a significant improvement compared to the control. The surface layer of C3 recorded the highest percentage increase in SIC of about 3.5 g kg^{-1} (0-10 cm depth) in a 2-year interval. There was a moderate (C2) and low-volume (C1) treatment with moderate levels of accumulation of SIC of 16.6 to 18.2 g kg^{-1} in the 0-30 cm layer and increasingly lower values at greater depths. SIC vertical distribution was mainly surface-oriented in the irrigated treatments and especially in C3 agreeing with the evaporative concentration and deposition of pedogenic carbonates at the soil surface.

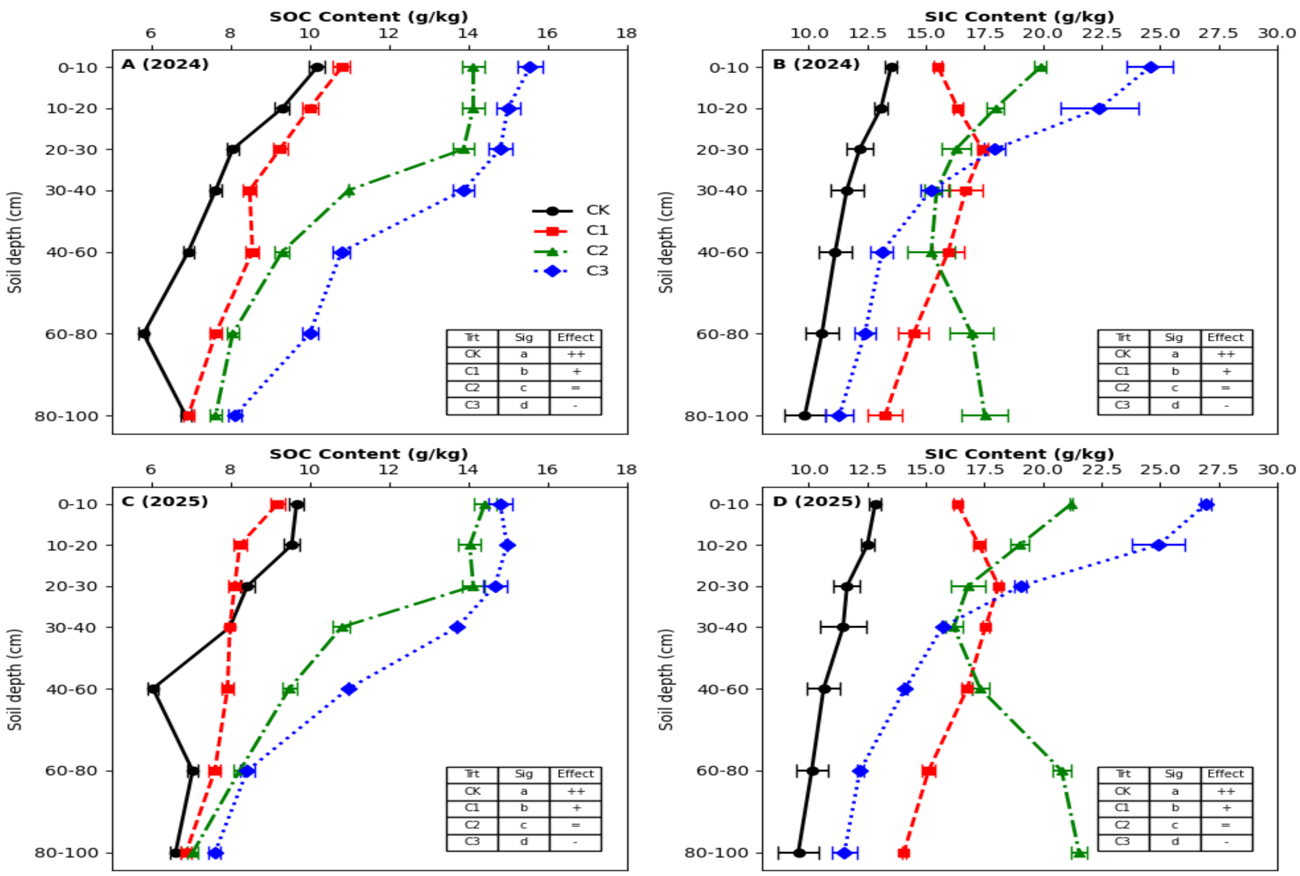

Fig. 3. Depth profiles of soil organic carbon (SOC) and soil inorganic carbon (SIC) concentration across irrigation treatments of year 2024-2025. Values are mean ± SE (n = 4) expressed in g kg^{-1}. Left panels show SOC; right panels show SIC. CK = rainfed control; C1 = 15 Lm^{-2} year^{-1}; C1 = 30 Lm^{-2} year^{-1}; C3 = 45 Lm^{-2} year^{-1}. Soil depths are presented at 0-10, 10-20, 20-30, 30-40, 40-60, 60-80, and 80-100 cm.

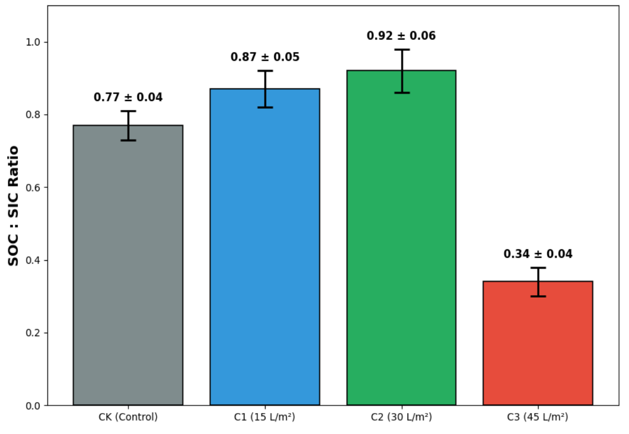

Fig. 4. Soil organic carbon to inorganic carbon (SOC:SIC) ratio in the 0-30 cm soil layer under different brackish irrigation treatments (two-year average). Values are mean ± SE (n=4). The dashed line at 1.0 indicates equal contribution of organic and inorganic carbon to the total soil carbon pool. C2 treatment shows the most balanced carbon pool, while C3 exhibits strong dominance of inorganic carbon.

SOC:SIC ratios and carbon pool quality: The SOC to SIC ratio was another very important indicator of the quality of carbon pools and that of the main sequestration mechanism. The control treatment showed SOC:SIC ratio of 0.77 ± 0.04 indicating a moderate proportion of organic carbon in the total soil carbon reservoir. Moderate irrigation produced the highest balance ratio of 0.92 ± 0.06 closely followed by high-volume treatment at 0.87 ± 0.05. The figures show a relatively strong combination of organic and inorganic carbon absorption. On the contrary, the high-volume treatment had the smallest ratio of 0.34 ± 0.04, indicating that it has undergone a significant shift to inorganic carbon dominance. The significant change in the SOC:SIC ratio under C3 had a strong and positive correlation with microbial biomass carbon ($r = 0.78$, $p<0.001$) and significant negative with soil bulk density ($r = 0.65$, $p<0.001$). It means that a higher proportion of organic to inorganic carbon pool is correlated with the increased levels of biological activity and physical development of the soil than a significant inorganic prevalence is linked to the impaired functions of microbes and poor physical organization of the soil (Fig. 4).

Statistical and multivariate analysis

Treatment effects and mixed models: The linear mixed-effects modeling revealed that the irrigation treatment exerted a significantly important fixed effect on all the measured soil and vegetation parameters ($p<0.001$). The level of variance due to treatment factor was substantial. It was 48% in electrical conductivity, 36% in soil pH, 41% in SOC and 39% in above ground biomass. Parallels of similar results indicated on the other hand, random effects involving plot duplication, amounted to less than 5% of total variation in the strength of consistency and reproducibility between treatment duplicates of the experiment. Tukey HSD tests revealed certain differences according to which EC showed considerable variation in all treatment pairs (C3 > C2 > C1 > CK); the pH of the soil in CK was significantly less than in all brackish treatments; aboveground biomass was significantly higher in C3 compared with other treatments; and SOC followed the clear order of C2 > C1 > CK > C3, with all pair-wise differences were significant.

Principal component analysis: Principal Component Analysis (PCA) was used effectively in the condensation of the multivariate response of the ecosystem and the first two principal components (PC1 and PC2) explained 76.5% of the total dataset variance. An axis of irrigation volume-inorganic carbon was defined by PC1 (48.8% variance) with significant positive loadings of EC (0.89), Na^+ concentration (0.87), and SIC (0.78), but negative loadings of the SOC:SIC ratio (-0.72) and species richness (-0.68). This axis clearly separated the C3 treatment (exhibiting high positive scores) from the remaining treatments, unambiguously associating it with elevated irrigation volume and inorganic carbon dominance. PC2 (27.7% variance) identified an axes of soil organic carbon-plant productivity with high positive loadings of SOC (0.85), above ground biomass (0.82), and vegetation cover (0.79) and negative loadings of bulk density (-0.65), and SAR (-0.61). The C2 treatment fitted perfectly on this axis, meaning that it had a unique combination of high SOC accumulation and intensive vegetative productivity. The PCA biplot represents a number of ecosystem clusters: CK in low-EC, moderate-productivity quadrant; C1 moving to high-productivity quadrant; C2 in ideal high-SOC/high-biomass quadrant and C3 in isolated high-inorganic-carbon low-biodiversity quadrant (Fig. 5).

Climate change implications and vulnerability: A study of climate change vulnerability focusing on the sustainability of the stored carbon depositories (IPCC, 2014), revealed the existence of big discrepancies between treatments (see to Supplementary Material of detailed methodologies). The C2 treatment also had the highest intrinsic climate mitigation potential (1,773 Mg CO_2-eq ha^{-1}), as well as, extraordinary sequestration sustainability (score of 1.0) and drought resilience (0.72). C2 treatment carbon pools showed the lowest value in temperature sensitivity (1.22) meaning that they were less prone to increased mineralization when expected warmer temperature was available. However, in contrast, the C3 treatment, although with a large inorganic carbon stock, showed high sensitivity of temperature (1.99) and low drought resistance (0.41), suggesting that its sequestration of carbon is quite vulnerable to the future climatic disruptions, in particular, to changes in precipitation and increased temperatures.

Discussion

The dual mechanisms of carbon sequestration in response to irrigation volume: This analysis shows a fundamental underpinning of duality about the response of soil carbon to saltwater water irrigation which is defined as the salinity sequestration paradox: the phenomenon whereby brackish irrigation increases total soil carbon storage but simultaneously degrades carbon pool quality and ecosystem function, with the direction and magnitude of this trade-off determined by irrigation volume. Although total soil carbon was improved due to the effect of the brackish irrigation compared to the rainfed control, the content and quality of carbon pool differed substantially as depending on the volume of irrigated soils. Intermediate irrigation (C2, 30 Lm^{-2} $year^{-1}$) has allowed maximum accretion of the soil organic carbon (SOC), particularly in deep strata (~39-51% greater than control), and has maintained a fairly steady SOC:SIC ratio (0.92 ± 0.06). It was attributed to decreased heterotrophic microbial growth and mineralization of organic matter (Trivedi *et al*., 2016; Yan *et al*., 2015), which is consistent with stoichiometric controls on microbial carbon-use efficiency (Manzoni *et al*., 2012; Kleber *et al*., 2015; Rowley *et al*., 2018). C2 is further evidence of a strong and functionally diverse ability to store carbon as shown by the almost optimum SOC:SIC ratio (Lehmann & Kleber, 2015; Cotrufo *et al*., 2013).

By contrast, high volume irrigation (C3, 45 Lm^{-2} $year^{-1}$) had a strong positive effect on the accumulation of soil inorganic carbon (SIC), and especially in the upper layers (~26.5 g kg^{-1}), resulting in a much lower ratio of SOC:SIC (0.34 ± 0.04). This signals a geochemically regulated sequestration process mediated by augmented levels of Na^+, Ca^{2+}, and HCO_3^-, as well as by elevated levels of evaporative demand, which convenes the environment conducive to the precipitation of carbonates by pedagogy (Zamanian *et al.,* 2021; Monger *et al*., 2015; Sanderman, 2012), mainly towards the soil surface in spite of the overall fallen pH (which was not so low as to inhibit the formation of carbonates). However, it also led to the net SOC losses in most of the upper layers during the two-year interval, which was arguably caused by the reduction in biomass-providing and a greater mineralization under severe salt stress (Deinlein *et al*., 2014; Munns & Tester, 2008; Schimel *et al*., 2007).

Interrelated irrigation volume and salt accumulation: This experimental design purposely incorporated brackish water with varying levels of application, and this stands as a practical factor in agriculture where the quality and availability of the sources of brackish water is limited. The presence of this whole treatment is used to show that the impacts of brackish irrigation are synergistic responses to stresses and not salinity only. The variance partitioning analysis results showed that mostly vegetative characteristics were constrained by the availability of water, and salts accumulated in the soil, influencing the chemical properties of the soil (Falkenmark *et al*., 2022; Liu *et al*., 2020). These higher sensitivity levels have significant administration consequences: the irrigation techniques should combine conditional volume limits considering the quality of water accessible as opposed to relying solely on overall volume constraints (Zhang *et al*., 2022).

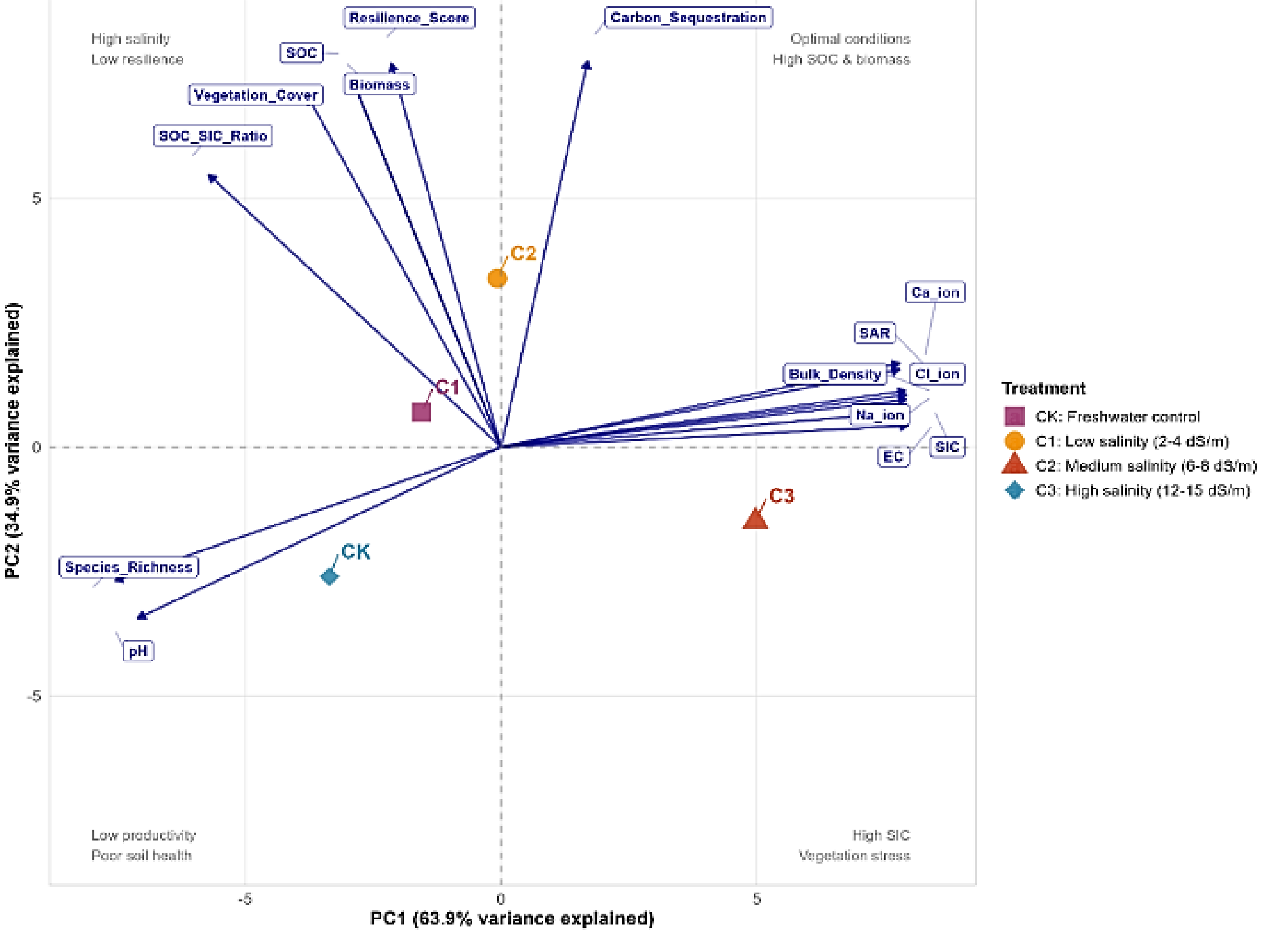

Fig. 5. Principal Component Analysis (PCA) biplot of ecosystem variables showing clustering by irrigation treatment. PC1 (48.8% variance) represents an irrigation volume-inorganic carbon axis; PC2 (27.7% variance) represents an organic carbon-plant productivity axis. Arrows indicate variable loadings; points represent individual treatment plots. CK = rainfed control; C1 = 15 L m^{-2} $year^{-1}$; C2 = 30 L m^{-2} $year^{-1}$; C3 = 45 L m^{-2} $year^{-1}$. EC = electrical conductivity; SOC = soil organic carbon; SIC = soil inorganic carbon; SAR = sodium adsorption ratio.

The C3 treatment ecological decline was not only attributed to salt concentration but also to the heightened synergistic stress because the high irrigation rate (45 Lm^{-2}) and brackish water application (5.76 dSm^{-1}) were beyond important ecological limits. This relationship was measured by path analysis and it is clear that as volume increases, salt stress becomes greater due to accumulation effects and has a direct effect on plant yield (Berdugo *et al*., 2020). This poses a great challenge to the management in dry areas: the lack of water that is to be addressed by the use of salty water at the same time hinders the ability of the system to tolerate the salt deposits (Qadir *et al*., 2021).

It can be concluded in the light of statistics that C2 treatment is a reasonable middle ground: a relatively high amount of irrigation (30 Lm^{-2}) including brackish water (5.76 dSm^{-1}) will strengthen the stability of carbon without damaging the ability to sustain the ecosystem (Bossio *et al*., 2020; Paustian *et al*., 2016). In case brackish irrigation becomes a necessity, the optimum of approximately 30 Lm^{-2} of brackish water with about 5-6 dSm^{-1} should be aimed at future irrigation systems should then incorporate the aspect of water quality and quantity in their decision-making processes and this poses the same questions in reciprocity; what can and cannot be the amount of brackish water to be used considering the soil conditions? And which water quality is to be taken depending upon the available quantities?

Transformation of soil physicochemical properties and vegetation response: Owing to brackish irrigation, significant changes in soil properties were made, and the reaction was directly influenced by them on plants. The gradual decrease of soil pH and rise of electrical conductivity showed evident dose-response (Figs. 1, 2) with the large-volume treatment (C3) causing the weakly alkaline levels of surface pH further to moderately alkaline, a tendency is consistent with the dilution effect of brackish water (pH 7.4), sodium build-up, bicarbonate addition, and potential ion reactions that reduce extreme alkalinity (Rengasamy, 2016; Slessarev *et al*., 2022).

Exchangeable sodium rose significantly and Sodium Adsorption Ratio (SAR) was 4.13 ± 2.04 at C3, which caused adverse effects in the structure of the soils. Positive interdependence of SAR indicated that sodium dispersion weakened the soil aggregation, resulting in increased compaction at the surface layers, thus hindering penetration of roots and water infiltration which are significant in the established reduction of the vegetation with the increase in irrigation volumes (Govers *et al*., 2017; Blake *et al*., 1986). The ecological drivers linking soil physico-chemical properties to microbial diversity patterns in dryland ecosystems have been shown to be strongly mediated by salinity (Ochoa-Hueso *et al*., 2018). The significantly lower SOC:SIC ratio under C3 (0.34) was significantly associated with negative correlation with soil bulk density ($r = -0.65$, $p<0.001$) and a positive value with microbial biomass carbon ($r = 0.78$, $p<0.001$), thus supporting the idea that the shifts towards the inorganic-dominated carbon storage are accompanied by the deterioration of the soil physical structure and reduced biological activity (Schmidt *et al*., 2011; Liang *et al*., 2017).

Carbon dynamics, thresholds, and sustainability of long-term sequestration: The results demonstrate that there is a clear biological threshold of saline-alkali grasslands when living under irrigation of brackish water, which lies at approximately 30-35 Lm^{-2} $year^{-1}$. Beneath this threshold (C1 and especially C2) added water is used to enhance primary output, SOC storage and to stabilize the SOC:SIC ratio (0.87-0.92) at quite a constant value, signifying the presence of both biological and geochemical carbon sequestration pathways (Bradford *et al*., 2019; Isbell *et al*., 2015). Crossing through this barrier (C3), the system undergoes rapid degradation: species richness decreases by 83%, aboveground biomass by 44%, and the SOC:SIC ratio drastically reduces to 0.34, which implies a virtually complete shift to the predominance of inorganic carbon in species (Bardgett *et al*., 2021; Berdugo *et al*., 2020). This shift leads to increased soil compaction, decrease of hydraulic conductivity, reduce microbial biomass, and a decrease in the ecosystem stability, which are congruent with the outcome of sodium-induced sodicity and intense osmotic/ionic stress of the vegetation community (Díaz *et al*., 2019; Scheffer *et al*., 2001).

Organic carbon is formed mainly by inorganic processes in the conditions of high irrigation; therefore, the reservoir is likely to be less stable in the long-term. Pedagenic carbonates are sensitive to soil pH, moisture conditions, as well as changes in land use (Zamanian *et al*., 2021; Monger *et al*., 2015). On the other hand, the more equalized organic-inorganic pool with moderate irrigation has the advantage of physical security in aggregates and biological stability with greater resilience to disturbance, and possibly greater security of carbon storage in the long term (Kleber *et al*., 2015; Cotrufo *et al*., 2013). These findings highlight the fact that intensive brackish irrigation advantages that are obtained through carbon sequestration at the expense of the different ecosystem services such as biodiversity, soil structure, water infiltration, and biological regulation, thus generating the need to focus on addressing ecosystem functionality rather than the amount of carbon held (Hooper *et al*., 2005; Oliver *et al*., 2015). Multiple global change factors, including salinity and altered water availability, interact to drive soil functions and microbial diversity in complex ways (Rillig *et al*., 2019).

Implications and future directions: The dilemma of salinity sequestration has a direct impact on the use of arid saline-alkali grasslands using brackish water on a sustainable basis. The most favorable trade-off in terms of SOC storage, at moderate irrigation volumes (about 20-35 Lm^{-2} $year^{-1}$, averaging 30 Lm^{-2} $year^{-1}$), and acceptable losses of biodiversity are moderate irrigation levels (30 Lm^{-2} $year^{-1}$) (Deinlein *et al*., 2014; Govers *et al*., 2017). The high-volume irrigation (≥ 45 Lm^{-2} $year^{-1}$) should be prevented, and it is above the critical point, which leaves wimpy, mainly inorganic carbon pools with highly ecological consequences (Zamanian *et al*., 2021). To determine at an early stage of threshold transgression, it is recommended that, soil electrical conductivity, sodium adsorption ratio as well as the ratio of soil organic carbon to soil inorganic carbon should be continuously monitored.

Where practicable, light watering procedures must be added with intermittent salt washing procedures or complementary measures of land amendments to improve structural solidarity and functionality (Gupta *et al*., 2020; Qadir *et al*., 2021). The next generation of research should focus on the long-term stability of inorganic carbon at high irrigation rates, the mediation of SOC:SIC ratio by microbes, and examination of the economic-ecological trade-offs between different types of saline-alkali grasslands with the view of improving the management practices of the region (Lal, 2020; Crowther *et al*., 2019), while recognizing that salt-affected soils globally represent both challenges and opportunities for bioenergy production and carbon sequestration (Wicke *et al*., 2011).

Conclusion

This study demonstrates that brackish water irrigation in saline-alkali grasslands increases total soil carbon but fundamentally alters carbon pool quality at high application volumes, revealing the salinity sequestration paradox. Moderate irrigation (30 L m^{-2} $year^{-1}$) optimized SOC accumulation in subsurface layers (~39-51% above control) and maintained a balanced SOC:SIC ratio (0.92), attributed to reduced microbial mineralization and enhanced calcium-organo complexation. However, species richness declined by 58% under this treatment. High-volume irrigation (45 L m^{-2} $year^{-1}$) crossed a critical ecological threshold: species richness fell by 83%, aboveground biomass by 44%, surface SOC declined, and pedogenic carbonate accumulation drove the SOC:SIC ratio to 0.34, indicating strong inorganic carbon dominance (~26.5 g kg^{-1} in the 0-10 cm layer). Brackish water irrigation decreased soil alkalinity in a volume-dependent manner, shifting control plot pH (8.24-9.01) toward moderately alkaline conditions at higher volumes, while simultaneously intensifying sodium-associated structural remodeling and inorganic carbon dominance. These findings carry direct management implications: irrigation volume and water quality must be jointly optimized. Strategies that prioritize total carbon storage while ignoring pool quality, biological activity, and ecosystem resilience risk producing climatically unstable, largely inorganic carbon sinks. Sustainable brackish water use should remain within approximately 20-35 L m^{-2} $year^{-1}$, a range that balances carbon sequestration benefits with the conservation of biodiversity, soil structure, and ecosystem function. The salinity sequestration paradox underscores that carbon pool quality, as captured by the SOC:SIC ratio, is as important as total carbon quantity for evaluating the long-term value of grassland carbon sinks.

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