Spatial Heterogeneity Characteristics of Soil Carbon and Its Influencing Factors in Populus euphratica Forests in the Lower Reaches of the Heihe River Postprint

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Abstract

The distribution of soil carbon in desert riparian forests is influenced by multiple factors. Taking the Ejina Oasis in the lower reaches of the Heihe River as the study area, this study investigated the spatial variation characteristics of soil organic carbon (SOC) and soil inorganic carbon (SIC) and their influencing factors by collecting soil samples from the 0–100 cm layer in 20 Populus euphratica forest sample plots. The results showed that: (1) The mean values of SOC and SIC in the 0–100 cm layer were 2.90 $g \cdot kg^{-1}$ and 10.79 $g \cdot kg^{-1}$, respectively, with SIC being 3.72 times that of SOC. (2) Both SOC and SIC decreased with increasing soil depth in the vertical direction. In the horizontal direction, although SOC and SIC both exhibited decreasing trends from the upper to lower reaches of the East River, the total SIC remained greater than SOC, indicating that SIC is the main storage form of soil carbon in the lower reaches of inland rivers in arid regions. (3) Soil physicochemical properties exhibited a high explanatory degree for SOC but a low explanatory degree for SIC. Among these, soil chemical properties (EC, Na^+, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, K^+) had the greatest influence on SOC. In summary, the soil carbon pool in the desert riparian forests of the lower Heihe River basin is dominated by SIC, with significant spatial variation in both horizontal and vertical directions, and the effects of soil physicochemical properties on the spatial variation of SOC and SIC differ. Specifically, alkaline cations are the primary factors influencing SOC, while soil sand content and bulk density are the primary factors influencing SIC.

Full Text

Spatial Differentiation and Its Influencing Factors of Soil Carbon in Populus euphratica Forest in the Lower Reaches of Heihe River

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Abstract

The distribution of soil carbon in desert riparian forests is influenced by multiple factors. Taking the Ejina Oasis in the lower reaches of the Heihe River as the study area, we investigated the spatial differentiation characteristics and influencing factors of soil organic carbon (SOC) and soil inorganic carbon (SIC) using soil samples from 20 Populus euphratica forest plots across 0–100 cm soil layers. The results show: (1) The mean SOC and SIC contents in the 0–100 cm soil layer were 2.90 $g \cdot kg^{-1}$ and 10.79 $g \cdot kg^{-1}$, respectively, with SIC being 3.72 times that of SOC, indicating that inorganic carbon is the main form of soil carbon in the lower reaches of inland rivers in arid regions. (2) Vertically, both SOC and SIC showed decreasing trends with increasing soil depth, while horizontally they decreased from the upper to lower sections of the East River, though the total SIC remained greater than SOC. (3) Soil physicochemical properties had high explanatory power for SOC but relatively lower explanatory power for SIC. Specifically, soil chemical properties such as electrical conductivity (EC), Na^+, $SO_4{}^{2-}$, Cl^-, Ca^{2+}, Mg^{2+}, and K^+ had the most significant influence on SOC. In conclusion, the soil carbon pool in desert riparian forests in the lower reaches of inland rivers in arid areas is predominantly composed of SIC, with notable spatial variations in both horizontal and vertical directions. Basic cations are the primary factor influencing SOC spatial differentiation, while soil sand content and bulk density are the key factors affecting SIC spatial differentiation.

Keywords: riparian Populus euphratica forest; soil carbon; distribution characteristics; influencing factors; Heihe River Basin

Introduction

Desert riparian forests are crucial ecosystems in arid and semi-arid regions, playing vital roles in maintaining regional ecological balance, conserving water resources, preventing wind erosion, and preserving biodiversity. In recent years, intensified global climate change and human activities have made these ecosystems increasingly vulnerable. Soil carbon pools, as important components of the carbon cycle, play a significant role in mitigating climate warming and maintaining ecosystem health. Changes in soil carbon storage serve as important indicators of the health, stability, and ecological security of desert riparian forest ecosystems.

Most current research on carbon pools in arid regions focuses on large-scale regional analyses, with particular emphasis on soil organic carbon (SOC) pools. However, soil inorganic carbon (SIC) is equally important in arid areas. Previous studies have estimated that the global SIC storage in the 0–100 cm soil layer is 470$\pm 7 Pg, while SOC storage is 578 \pm 8 Pg, demonstrating that SIC and SOC are of comparable importance inar$
Pg of SOC, accounting for 47.00% of the national total. Clarifying the interactions and distribution characteristics of SOC and SIC in arid regions is essential for understanding carbon pool dynamics.

Populus euphratica, a typical tree species in desert riparian forests of northwest China, has received attention regarding its role in soil carbon storage. However, existing research has primarily focused on plant diversity, responses to soil salinity and nutrient regulation, and the effects of ecological water conveyance on forest restoration, with less attention paid to soil carbon pools, particularly SIC. Local-scale studies have shown that abiotic factors such as soil basic cations, particle size, and clay content directly affect soil carbon storage. Therefore, systematically analyzing the spatial differentiation characteristics of soil carbon in P. euphratica forests and exploring their influencing factors is critical for understanding carbon cycling processes and assessing the role of these forests in regional carbon balance.

A previous study by Chen et al. measured total carbon content in the 0–280 cm soil layer of P. euphratica forest in the lower Heihe River as 20.23$\pm 2.36 g \cdot kg^{-1}$. However, their survey plots were located at the oasis edge, resulting in poor spatial representativeness. Broader surveys are needed to obtain distribution characteristics of soil carbon in P. euphratica forests. This study takes the desert riparian forest ecosystem dominated by P. euphratica in the Ejina Oasis of the lower Heihe River as a case study. In May 2022, we conducted soil surveys and analyses at 20 P. euphratica forest plots at the Alxa Desert Eco-Hydrology Experimental Research Station. Our objectives were to reveal the spatial differentiation characteristics of SOC and SIC and identify environmental factors influencing soil carbon distribution using environmental data. The findings will help understand key processes in arid region carbon cycling and provide data support for carbon management strategies under global climate change.

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1. Materials and Methods

1.1 Study Area Overview The study area is located in the Ejina Oasis (41°40 -42°40 N, 100°15 -101°15 E), which represents China' s second-largest natural P. euphratica forest distribution area and forms an alluvial delta at the terminus of the Heihe River. The oasis covers an area of 3,445 km^2 with an extremely arid climate. Annual precipitation is 36.50 mm, average annual evaporation is 2,094.20 mm, the aridity index (precipitation/evaporation) is less than 0.05, average annual temperature is 9.36°C, and average annual relative humidity is 34%. The terrain is flat with a gentle slope.

The Heihe River (called the Ejina River in its lower reaches) splits at Langxinshan into eastern and western branches, forming seven tributaries that eventually flow into the East and West Juyanhai Lakes. Vegetation is dominated by temperate broadleaf deciduous forest, with P. euphratica being the only arboreal constructive species. Influenced by river distribution in the lower Heihe River, P. euphratica is mainly distributed along the banks of the East and West Rivers and in lacustrine plain areas. Soils in the riparian zone are primarily fluvo-aquic soils, while downstream natural oasis soils are mainly gypsum gray-brown desert soils and forest meadow soils.

1.2 Plot Setup and Soil Sampling We selected 20 typical desert riparian P. euphratica forest plots in the study area, considering uniform distribution and accessibility while avoiding main traffic arteries. Given the influence of water conveyance projects in the Heihe River, survey plots were arranged parallel or perpendicular to the riverbanks, numbered H1-H20. Field vegetation surveys and soil sampling were conducted in May 2022. For each plot, we randomly selected 10 trees with diameter at breast height (DBH) >130 cm, measured in ascending order of DBH. Measurements included tree height, DBH, and four-direction crown width. Tree height was measured using a Haglof Vertex IV hypsometer (Sweden), DBH using diameter tapes, and crown width using measuring tapes.

Normalized Difference Vegetation Index (NDVI) was calculated using near-infrared (NIR) and red (R) bands from Landsat 8 OLI/TIRS imagery (http://www.gscloud.cn) from June 2022 with cloud cover <5%: NDVI = (NIR - R)/(NIR + R). Soil samples were collected using soil profile excavation, with stratified sampling at 0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm depths. Collected soil samples were divided into two categories: (1) aluminum box and ring knife samples for soil water content and bulk density determination, and (2) samples for soil particle size composition, salinity, and nutrient content analysis. The latter were air-dried, roots and gravel removed, passed through a 2 mm sieve, and stored for analysis.

1.3 Soil Physicochemical Index Determination Soil water content (SWC) was measured by oven-drying at 105°C, and soil bulk density (BD) by the ring knife method. Soil pH and electrical conductivity (EC) were measured using a Seven Multi-parameter analyzer (USA) with a soil:water ratio of 1:5, shaken for 15 minutes and left to stand for 30 minutes before measuring the supernatant. Soil sand, silt, and clay contents were determined using a Malvern Mastersizer 3000 particle size analyzer (UK) following USDA soil particle classification standards: clay (<0.002 mm), silt (0.002-0.05 mm), and sand (0.05-2.00 mm).

Soil organic carbon (SOC) was measured using the potassium dichromate external heating method, and soil inorganic carbon (SIC) was calculated from total carbon content measured with a CN802 carbon-nitrogen element analyzer (Italy). Soil cation (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anion (Cl^-, SO_4^{2-}) contents were measured using a DIONEX ion chromatograph (USA). Before analysis, soil samples were mixed with water at a 1:5 ratio, stirred repeatedly for 5 days, left to clarify, and the supernatant was taken for measurement.

1.4 Data Analysis To reveal vertical distribution characteristics, we used Excel for statistical analysis and non-parametric rank-sum tests in SPSS 26.0 to analyze differences among soil depths, with Dunn' s multiple comparisons for significance testing. To reveal horizontal distribution patterns, the 20 plots were divided into four regions: (1) West River mainstream riparian zone (H1-H5), (2) East River middle-upper riparian zone (H6-H10), (3) East River lower riparian zone (H11-H15), and (4) East River lower oasis core area (H16-H20).

To explore relationships between environmental factors and soil carbon content in desert riparian forests, we used linear regression and dimensionality reduction analysis. The relative importance of environmental factors was analyzed using the relaimpo package in R Studio. To assess the explanatory power of environmental factors on SOC and SIC, variance partitioning was performed using the vegan package in R. Path analysis was conducted in Amos 26.0 to determine the mechanisms affecting soil carbon component contents.

2. Results

2.1 Vertical Variation Characteristics of Soil Carbon Components Analysis of vertical changes in soil carbon in the lower Heihe River P. euphratica forest (Table 1) showed that SOC and SIC contents generally decreased with increasing soil depth. SOC contents differed significantly among depths ($P < 0.05$), with significant differences between 0-10 cm and 60-80 cm, 0-10 cm and 80-100 cm, 10-20 cm and 60-80 cm, and 10-20 cm and 80-100 cm layers. SIC contents also showed significant differences ($P < 0.05$) between 0-10 cm and 20-40 cm, 0-10 cm and 40-60 cm, 0-10 cm and 60-80 cm, and 0-10 cm and 80-100 cm layers. The mean SOC contents were

10.79$±1.09, 6.22±1.18, 3.38±0.55, 2.28±0.29, 2.13±0.29, and1.93±0.45g · kg^{-1}$ for 0-10, 10-20, 20-40, 40-60, 60-80, and 80-100 cm layers, respectively. The mean SIC contents were 10.79$±0.68, 12.87±1.71, 11.69±0.76, 10.89±0.75, 10.98±0.82, and9.11±1.05g· kg^{-1}, respectively.TheSIC : SOCratioswere3.87±0.65, 5.01±0.63, 5.80±0.52, 6.29±0.53, 6.77±0.65, and7.8
respectively.

2.2 Horizontal Variation Characteristics of SOC and SIC Horizontal variation analysis of soil carbon in the lower Heihe River P. euphratica forest (Table 2) showed that SOC and SIC contents gradually decreased from the upper to lower sections of the East River riparian zone and then to the lower oasis core area. SOC and SIC contents in the West River mainstream riparian zone were roughly equivalent to those in the East River lower riparian zone. SOC contents were higher in the East River middle-upper and lower riparian zones, moderate in the East River lower oasis core area, and lowest in the West River mainstream riparian zone. In contrast, SIC contents were highest in the East River lower oasis core area, moderate in the East River middle-upper and lower riparian zones, and lowest in the West River mainstream riparian zone.

The SIC:SOC ratio showed a decreasing trend from the upper to lower sections of the East River. The proportion of SIC in the 0-100 cm layer varied from 21-30% in the West River mainstream riparian zone, 10-37% in the East River middle-upper riparian zone, 11-23% in the East River lower riparian zone, and 27-30% in the East River lower oasis core area. This indicates that soil carbon in the lower Heihe River P. euphratica forest exists mainly as inorganic carbon.

2.3 Relationship Between Soil Carbon Content and Physicochemical Factors Analysis of vertical changes in soil environmental factors (Table 3) showed that SWC and BD initially increased then decreased with depth, while EC showed the opposite trend. Clay and silt contents increased with depth, whereas sand content decreased. Conversely, soil ion contents decreased with depth.

Correlation analysis revealed that SOC was significantly correlated with soil physicochemical indices but not with vegetation indices. Specifically, among soil indicators, all ions except K^+ were significantly correlated with SOC. Similarly, SIC was significantly correlated with soil physicochemical indices but not vegetation indices, showing significant correlations with BD, clay, and soil ions (Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, ${SO_4}^{2-}$).

Linear regression analysis showed that SOC had extremely significant relationships with EC, Cl^-, and ${SO_4}^{2-}$ ($P < 0.001$). SIC showed extremely significant positive linear relationships with BD and ${SO_4}^{2-}$, and extremely significant negative relationships with clay and Cl^- ($P < 0.001$). The relative importance of environmental factors was significant (Figure 4), with soil chemical properties showing the highest importance for predicting SOC changes, and BD and ${SO_4}^{2-}$ showing significant importance for predicting SIC changes.

Further linear regression analysis (Figures 5 and 6) and variance partitioning (Table 5) showed that environmental factor combinations explained SOC and SIC variation as follows: soil physical, chemical, and comprehensive properties explained 72.00% of SOC variation; soil physical and chemical properties explained 32.00% of SIC variation. In structural equation modeling (Figure 7), soil chemical properties had the strongest positive effect on SOC (path coefficient = 0.65), followed by comprehensive properties (0.42), while soil physical properties had a negative effect (−0.32). For SIC, both soil physical and chemical properties showed negative relationships (−0.38 and −0.45, respectively), with chemical properties having a stronger influence. The effect path coefficient from comprehensive properties to SIC was +0.62.

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3. Discussion

3.1 Variation of Soil Carbon Content in P. euphratica Forest Area

In the 0-20 cm soil layer, SOC content (4.80 ± 0.87 g · kg^{-1}) in our study area was higher than that in wasteland with the same soil type in the Yutian Oasis farmland periphery of the Tarim Basin (2.29 g · kg^{-1}), mainly due to better vegetation cover. Conversely, SIC content (10.04 ± 0.90 g · kg^{-1}) was much lower than in the Yutian Oasis (25.86 g · kg^{-1}), primarily because the Ejina Oasis has lower calcium and other carbonate minerals in its soil parent material, and irrigation water from the Heihe River has lower salinity than snowmelt water in the Tarim Basin, leading to differences in carbonate accumulation.

The SIC:SOC ratio in the 0-20 cm layer differed substantially from results in Xinjiang' s farmland and desert ecosystems, where SIC proportions were 35.30% and 23.10-24.60%, respectively. In the Ejina Oasis, SIC proportions were 10.57-13.91% in the 0-20 cm layer and 45.23-59.37% in the 0-100 cm layer, while Xinjiang' s farmland and desert ecosystems showed 27.30% and 15.80-17.50%, respectively. The higher SOC in the Ejina Oasis is attributed to higher biomass and organic matter input from P. euphratica and other vegetation, coupled with better ecological protection measures that maintain surface SOC. The low decomposition rate in arid environments facilitates organic matter accumulation in surface layers.

Vertically, the decreasing SOC with depth is a typical characteristic of forest ecosystems, as organic carbon primarily originates from surface litter and root exudates that are difficult to transport to groundwater. This pattern was confirmed in studies of soil carbon vertical distribution in the southern Tarim Basin. Strong evaporation leads to surface enrichment of soil salts, which form SIC through chemical processes. The surface enrichment of SIC is also evident, with low bulk density (1.20 g · cm^{-3}) in surface soils providing better aeration and permeability that facilitates microbial activity and plant litter decomposition, resulting in higher surface SOC.

However, studies have shown that increased salinity inhibits calcium carbonate formation, consistent with our finding that soil chemical properties negatively affect SIC. While SIC should theoretically increase with depth (contrary to salt distribution), our results show SIC slightly decreases with depth, possibly because our sampling depth (0–100 cm) did not capture significant differences in abiotic factors like CO_2 partial pressure. The most likely explanation is that shallow groundwater depth in P. euphratica forests allows deep-layer Ca^{2+} ions to dissolve and migrate to shallow groundwater. This is supported by the slight increase in SIC in 0–80 cm layers and the decrease in 80–100 cm layers. For desert riparian forests relying on groundwater, SIC vertical distribution is closely related to groundwater depth.

Horizontally, SOC and SIC showed decreasing trends from the upper to lower sections of the East River, though differences were not significant. Only soil BD showed significant horizontal differences, while other potential influencing factors like Cl^- and ${SO_4}^{2-}$ showed no clear variation. Hydrologically-driven water erosion selectively transports fine particles, preferentially moving lighter components (SOC) from surface soils. Flooding causes considerable SOC loss, particularly evident in the decreasing SOC trend. High-porosity soils promote organic acid production and Ca^{2+} chelation, facilitating Ca^{2+} binding with ${CO_3}^{2-}$ to form $CaCO_3$ precipitation, which may explain the increasing SIC trend. These combined factors result in the observed horizontal distribution patterns of soil carbon in P. euphratica forests.

3.2 Influencing Factors of Soil Carbon Content in P. euphratica Forest Area Soil physicochemical properties significantly influence SOC and SIC in the study area, with complex interactions between SOC and SIC. Our results show that SOC increase promotes SIC accumulation, consistent with positive correlations found in artificial forests of the Mu Us Sandy Land. This occurs through two mechanisms: (1) Physical deposition—Heihe River water carries sediment rich in Ca^{2+} that deposits during flooding, enriching surface soil Ca^{2+}; (2) Chemical deposition—biological decomposition increases soil CO_2 partial pressure, which interacts with Ca^{2+}-rich minerals to form secondary carbonates, improving soil structure and affecting SIC formation. Thus, SIC formation is complex, influenced by both abiotic and biotic factors, with SOC-SIC transformation accounting for substantial soil carbon content variation.

In horizontal distribution, soil physical properties showed negative effects on SOC, likely because sandy soils dominate the study area with low silt and clay contents that are unfavorable for aggregate formation. Soil chemical properties (particularly salinity) had the greatest influence on SOC, with physical properties ranking second. At high ion concentrations, soil salinity protects SOC by promoting its binding with soil particles through cation bridging, which limits microbial decomposition. The net effect of soil physicochemical properties on SOC represents a balance between positive and negative influences.

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4. Conclusion

As a typical arid region, the lower Heihe River area exhibits representative soil carbon cycling characteristics. Studying this region not only reveals the uniqueness of soil carbon distribution in arid areas but also provides insights for similar regions. Based on soil investigations of 20 P. euphratica forest plots, our main conclusions are:

1) In desert riparian forest ecosystems dominated by P. euphratica in arid regions, soil carbon in the 0–100 cm layer exists primarily as inorganic carbon. Vertically, SOC and SIC decrease with depth, with SOC showing a more pronounced decline. Horizontally, both SOC and SIC decrease from the upper to lower sections of the East River, with SOC again showing a more obvious decreasing trend. Future research should increase sampling depth and investigate groundwater depth to further understand soil carbon spatial differentiation.

2) Soil chemical properties (EC, Na^+, $SO_4{}^{2-}$, Cl^-, Ca^{2+}, Mg^{2+}, K^+) are more important than physical properties in controlling soil carbon in desert riparian forest ecosystems of arid regions, with significantly greater influence on SOC than SIC. Therefore, chemical properties cannot be ignored when estimating soil carbon in these ecosystems.

References

[9] Song X D, Yang F, Wu H Y, et al. Significant loss of soil inorganic carbon at the continental scale[J]. National Science Review, 2021, 9(2): nwab120, doi: 10.1093/nsr/nwab120.

[10] Sparks D L. Advances in agronomy[M]. London: Academic Press, 2023: 229-265.

[11] Huang Y Y, Song X D, Wang Y P, et al. Size, distribution, and vulnerability of the global soil inorganic carbon[J]. Science, 2024, 384(6692): 233-239.

[12] Yusup A, Halik Ü, Abliz A, et al. Population structure and spatial distribution pattern of Populus euphratica riparian forest under environmental heterogeneity along the Tarim River, northwest China[J]. Frontiers in Plant Science, 2022, 13: 844819, doi: 10.3389/fpls.2022.844819.

[13] Peng Y, He G J, Wang G Z. Spatial and temporal analysis of the changes in Populus euphratica distribution in the Tarim National Nature Reserve over the past 60 years[J]. International Journal of Applied Earth Observation and Geoinformation, 2022, 113: 103000, doi: 10.1016/j.jag.2022.103000.

[14] Gao X Y, Hao H C, Zhang X Q, et al. Responses of vegetation water use efficiency to meteorological factors in arid areas of northwest China: A case of Xinjiang[J]. Arid Land Geography, 2023, 46(7): 1111-1120.

[15] Han L, Feng Y, Li Y K, et al. Effects of groundwater depth on carbon, nitrogen, phosphorus ecological stoichiometric and homeostasis characteristics of Populus pruinosa leaves and soil in Tarim Basin, Xinjiang, China[J]. Chinese Journal of Plant Ecology, 2024, 48(1): 92-102.

[16] Zhang T J, Chen Y N, Ali S. Abiotic stress and human activities reduce plant diversity in desert riparian forests[J]. Ecological Indicators, 2023, 152: 110340, doi: 10.1016/j.ecolind.2023.110340.

[17] Yang Y H, Li W H, Li H M, et al. Impacts of degraded ecosystem restoration on soil organic carbon in inland basin of Tarim River[J]. Chinese Journal of Soil Science, 2010, 41(4): 855-859.

[18] Wang Z, Li J L, Zhang J D, et al. Influences of ecological water conveyance on Populus euphratica forest restoration in the middle reaches of Tarim River[J]. Arid Land Geography, 2023, 46(1): 94-102.

[19] Ma J L, Shi J H, Wang X Y, et al. Effects of flood overflow on soil organic carbon and active components of Populus euphratica forest in the middle reaches of the Tarim River[J]. Arid Zone Research, 2023, 40(8): 1248-1257.

[20] Shi Y F, Xue X, You Q G, et al. Distribution characteristics of soil organic carbon and its relationship with soil physical properties in Ali Desert area, Tibetan Plateau[J]. Journal of Desert Research, 2023, 43(3): 284-294.

[21] Dong L W, Sun Y, Ran J Z, et al. Ecosystem organic carbon storage and their drivers across the drylands of China[J]. Catena, 2022, 214: 106280, doi: 10.1016/j.catena.2022.106280.

[22] Wei G R, Zhang C L, Li Q, et al. An evaluation of topsoil carbon storage in Chinese deserts[J]. Science of the Total Environment, 2023, 872: 162284, doi: 10.1016/j.scitotenv.2023.162284.

[23] Zhang Z P, Ding J L, Zhu C M, et al. Changes in soil organic carbon stocks from 1980–1990 and 2010–2020 in the northwest arid zone of China[J]. Land Degradation & Development, 2022, 33(15): 2713-2727.

[24] Chen Y Q, Xi H Y, Cheng W J, et al. Characteristics of soil carbon and nitrogen change in three typical plant communities in desert riparian forest area[J]. Journal of Desert Research, 2023, 43(1): 150-159.

[25] Plaza C, Zaccone C, Sawicka K, et al. Soil resources and element stocks in drylands to face global issues[J]. Scientific Reports, 2018, 8: 13788, doi: 10.1038/s41598-018-32229-0.

[26] Lal R. Carbon sequestration in dryland ecosystems[J]. Environmental Management, 2004, 33(4): 528-544.

[27] Yu T F, Feng Q, Si J H, et al. Flooding constrains tree water use of a riparian forest in the lower Heihe River Basin, northwest China[J]. Science of the Total Environment, 2021, 760: 144069, doi: 10.1016/j.scitotenv.2020.144069.

[28] Zhang G L, Gong Z T. Soil survey laboratory methods[M]. Beijing: Science Press, 2011: 47-70.

[29] Bao S D. Soil and agricultural chemistry analysis[M]. Beijing: China Agriculture Press, 2000: 120-147.

[30] Gong L, Zhu M L, Liu Z Y, et al. Correlation among soil organic carbon, soil inorganic carbon and environmental factors in a typical oasis in the southern edge of the Tarim Basin[J]. Environmental Science, 2016, 37(4): 1516-1522.

[31] Yang Y, Zhang X Y, Su W, et al. Soil organic carbon storage and its influencing factors in farmland and desert ecosystems in Xinjiang[J]. Acta Ecologica Sinica, 2024, 44(14): 1-12.

[32] Hou H, Zhang S Z, Guan J H, et al. Accumulation of soil organic carbon and total nitrogen in Quercus aliena var. serrata forests at different age stages in the Xiaolongshan Mountains, Gansu Province[J]. Acta Ecologica Sinica, 2016, 36(24): 8025-8033.

[33] Harley A D, Gilkes R J. Factors influencing the release of plant nutrient elements from silicate rock powders: A geochemical overview[J]. Nutrient Cycling in Agroecosystems, 2000, 56: 11-36.

[34] Pan J X, Wang J S, Tian D S, et al. Biotic factors dominantly determine soil inorganic carbon stock across Tibetan alpine grasslands[J]. Soil, 2022, 8(2): 687-698.

[35] Gao Y, Dang P, Zhao Q X, et al. Effects of vegetation rehabilitation on soil organic and inorganic carbon stocks in the Mu Us Desert, northwest China[J]. Land Degradation & Development, 2018, 29(4): 1031-1040.

[36] Luo Q, Wang Y G, Deng C Y, et al. Distribution of inorganic carbon in soil profile and its relationship with soil saline-alkali property in arid area[J]. Journal of Soil and Water Conservation, 2017, 31(5): 240-246.

[37] Zhang Y H, Liu C, Fu Z Y, et al. Research progress of hydrological process and soil organic carbon migration in slope field[J]. Chinese Journal of Soil Science, 2023, 54(3): 730-738.

[38] Zhou H, Gan F L, Dai Q H, et al. Migration of dissolved carbon on bare karst slopes in soil in response to natural rainfall events[J]. Geoderma, 2023, 436: 116527, doi: 10.1016/j.geoderma.2023.116527.

[39] Hassani A, Smith P, Shokri N. Negative correlation between soil salinity and soil organic carbon variability[J]. Proceedings of the National Academy of Sciences, 2024, 121(18): e2317332121, doi: 10.1073/pnas.2317332121.

[40] Yang R M, Yang F. Impacts of Spartina alterniflora invasion on soil inorganic carbon in coastal wetlands in China[J]. Soil Science Society of America Journal, 2020, 84(3): 844-855.

[41] Huang P, Zhang J B, Xin X L, et al. Proton accumulation accelerated by heavy chemical nitrogen fertilization and its long-term impact on acidifying rate in a typical arable soil in the Huang-Hai Plain[J]. Journal of Integrative Agriculture, 2015, 14(1): 148-156.

[42] Tong L S, Fang N F, Xiao H B, et al. Sediment deposition changes the relationship between soil organic and inorganic carbon: Evidence from the Chinese Loess Plateau[J]. Agriculture, Ecosystems & Environment, 2020, 302: 107076, doi: 10.1016/j.agee.2020.107076.

[43] de Nijs E A, Cammeraat E L. The stability and fate of soil organic carbon during the transport phase of soil erosion[J]. Earth Science Reviews, 2020, 201: 103067, doi: 10.1016/j.earscirev.2019.103067.

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