Carbon Dynamics in the Plant-Soil System During Wind Erosion Pit Development in Sandy Grasslands: A Case Study of Xilingol League (Postprint)

Authors: Lü Nan, Ge Nan, Wang Bo, Li Yuwei, Yu Yanan, Li Xin, Wang Chuanqi

Date: 2025-09-17T19:45:42+00:00

Abstract

Grassland wind-erosion pits alter plant growth environments and influence carbon cycling processes in grassland ecosystems. From April to October 2022, in the sandy grassland of Duolun County, Xilingol League, Inner Mongolia Autonomous Region, the space-for-time substitution method was employed to investigate the effects of wind-erosion pit development on carbon dynamics in the plant-soil system, analyzing the spatiotemporal differentiation characteristics and environmental responses of soil physicochemical properties, plant and soil carbon storage, and soil carbon-containing gas fluxes. The results demonstrated: (1) Wind-erosion pit development significantly reduced total plant biomass and total plant carbon storage, with decreases of 97.09% and 95.48%, respectively, particularly during the active wind-erosion pit stage. (2) Soil carbon pool losses were most pronounced during the active wind-erosion pit stage, with soil organic carbon, microbial biomass carbon content, and total carbon content decreasing by 63.53%, 74.58%, and 61.08%, respectively. (3) Wind-erosion pit development significantly decreased soil greenhouse gas fluxes; during the active wind-erosion pit stage, cumulative soil CO2 emissions declined by an average of 60.99%; concurrently, soil CH4 uptake decreased by an average of 88.89% and transitioned from uptake to release during May-June. (4) Wind-erosion pit development primarily influenced the stability of the plant-soil system carbon pool by altering structural indicators such as soil bulk density and porosity. In conclusion, wind-erosion pit development substantially modified carbon dynamics in the sandy grassland plant-soil system, causing severe losses to plant and soil carbon pools and intensifying soil impoverishment.

Full Text

Carbon dynamics of the plant-soil system during the development of wind erosion pits in sandy grasslands: A case study of the Xilin Gol League grassland

LYU Nan[1], GE Nan[2], WANG Bo[1], LI Yuwei[1], YU Yanan[1], LI Xin[1], WANG Chuanqi[1]

[1]College of Geographic Sciences, Inner Mongolia Normal University, Hohhot 011517, Inner Mongolia, China
[2]Institute of Water Resources for Pasturing Area of the Ministry of Water Resources, Hohhot 010020, Inner Mongolia, China

Abstract

Wind erosion pits in grasslands alter plant growth environments and affect carbon cycling processes in grassland ecosystems. From April to October 2022, we investigated the effects of wind erosion pit development on carbon dynamics in plant-soil systems in the sandy grassland of Duolun County, Xilin Gol League, Inner Mongolia Autonomous Region, using the spatiotemporal substitution method. We analyzed the spatiotemporal heterogeneity and environmental responses of soil physicochemical properties, plant and soil carbon storage, and soil carbon-containing gas fluxes. The results showed that: (1) Wind erosion pit development significantly reduced total plant biomass and total plant carbon storage, with decreases of 97.09% and 95.48%, respectively, particularly during the active blowout stage. (2) The soil carbon pool experienced the most significant loss during the active blowout stage, with soil organic carbon, microbial biomass carbon, and total carbon content decreasing by 63.53%, 74.58%, and 61.08%, respectively. (3) Wind erosion pit development significantly reduced soil greenhouse gas fluxes. During the active blowout stage, cumulative CO_2 emissions decreased by an average of 60.99%; simultaneously, soil CH_4 absorption decreased by an average of 88.89% and shifted from absorption to release during May-June. (4) Wind erosion pit development primarily affected the stability of the plant-soil system carbon pool by altering structural indicators such as soil bulk density and porosity. In summary, wind erosion pit development significantly altered carbon dynamics in the plant-soil system of sandy grasslands, causing severe losses in plant and soil carbon pools and exacerbating soil impoverishment.

Keywords: soil carbon pool; plant carbon pool; soil greenhouse gas; grassland wind erosion pit

1.1 Study area overview

The study area is located in Duolun County, Xilin Gol League, southeastern Inner Mongolia (41°46 -42°36 N, 115°51 -116°54 E) [Figure 1: see original paper]. The region has an elevation of 1150–1800 m and features a semi-circular basin topography that is higher at the periphery and lower in the center. The climate is a typical continental climate transitioning from temperate semi-arid to semi-humid, with an annual average temperature of 1.6°C and annual precipitation of 385 mm concentrated in the growing season (approximately 100 days). Winters are long and cold, summers are cool and brief, and the area receives abundant sunlight with concurrent heat and moisture. The dominant soil types are chestnut soil, meadow soil, and aeolian sandy soil. Duolun County lies in the transition zone between meadow steppe and typical steppe, with rich grassland vegetation types and extensive grassland resources .

1.2 Experimental design

This study selected wind erosion pits in Duolun County as the research object and conducted field experiments from April to October 2022. Based on the research of Zhang et al. and considering the topography, soil development, vegetation types, and coverage of the study area, the sample plots were divided into four types: natural grassland, wind-eroded bare land, active blowout, and extinct blowout. Natural grassland formed under natural conditions without significant human disturbance, dominated by herbaceous plants with fertile soil and relatively stable ecological conditions. Wind-eroded bare land formed due to overgrazing and unreasonable agricultural activities, where surface vegetation destruction led to soil exposure, presenting patchy distributions ranging from small bare areas to large contiguous patches. Active blowouts experienced continuous wind erosion of fine materials, with soil layers collapsing under gravity due to lack of vegetation and fine particle support, accelerating wind erosion speed and volume, forming dish-shaped or bowl-shaped pits. As erosion intensified on side walls and edges, blowouts gradually merged to form giant trough-shaped pits. Extinct blowouts occurred when environmental conditions improved, slowing or stopping blowout development, with vegetation gradually covering pit walls, slopes becoming gentler, depths decreasing, and shapes becoming smoother and flatter, allowing ecological functions to gradually recover. These types constitute a wind erosion succession sequence, demonstrating different stages of geomorphic evolution with significant temporal continuity and spatial representativeness, meeting the requirements of the spatiotemporal substitution method through multi-point selection and high-frequency monitoring.

In each plot, we established 20 m × 20 m rectangular sample plots. Within each rectangular plot, we randomly set up 1 m × 1 m herbaceous quadrats for measuring plant biomass. Simultaneously, we randomly excavated 80 cm soil profiles in each rectangular plot.

1.3 Plant and soil sample collection and analysis

We conducted biomass surveys in each herbaceous quadrat in mid-July, mid-August, and mid-September 2022. Aboveground biomass was measured using the clipping method, while belowground root biomass was measured using the complete excavation method. Collected plant samples were partially weighed fresh, then placed in an oven at 105°C for 30 minutes to kill the plants, followed by drying at 80°C to constant weight to obtain dry weight for calculating aboveground biomass. Another portion was washed, dried, ground, sieved, and subsampled to determine organic carbon content in aboveground parts, belowground parts, and litter, then calculate carbon storage in each component and total plant carbon storage.

Each soil profile was divided into four layers (0–20 cm, 20–40 cm, 40–60 cm, and 60–80 cm). In each layer, three replicate points were selected to measure soil water content, field capacity, bulk density, and porosity using the ring knife method. Simultaneously, one soil sample was collected from each layer and stored in an aluminum box for laboratory analysis. Collected soil samples were dried, sieved, mixed, and subsampled for various index measurements. Soil particle size composition was measured using a Bettersize 3000 Plus laser particle size analyzer. pH was measured using a Leici PHS-3C portable soil pH meter. Soil total carbon content was measured using an elemental analyzer. Soil organic carbon content was measured using an organic carbon analyzer. Soil inorganic carbon content was measured using the gasometric method. Soil microbial biomass carbon content was first extracted using the chloroform fumigation method, then the organic carbon content in the extract was measured using an organic carbon analyzer.

Soil carbon storage indicators were calculated using the following formulas:

$$SOC = \sum_i \frac{C_i \times D_i \times H_i \times (1 - G_i)}{100} \times 100$$

$$SIC = \sum_i \frac{C_i \times D_i \times H_i \times (1 - G_i)}{100} \times 100$$

$$TC = \sum_i \frac{C_i \times D_i \times H_i \times (1 - G_i)}{100} \times 100$$

where SOC, SIC, and TC represent soil organic carbon, inorganic carbon, and total carbon storage ($\mathrm{t \cdot hm^{-2}}$), respectively; C_i represents the organic carbon, inorganic carbon, or total carbon content of the i-th soil layer ($\mathrm{g \cdot kg^{-1}}$); D_i represents the bulk density of the i-th soil layer ($\mathrm{g \cdot cm^{-3}}$); H_i represents the thickness of the i-th soil layer (cm); and G_i represents the gravel volume content of the i-th soil layer (%).

1.4 Carbon-containing gas measurement

To determine the effect of wind erosion pit development on soil carbon emissions, three soil gas sampling points were randomly set up in each rectangular plot at the end of May 2022. The static dark chamber method was used for sampling [18]. The static dark chamber consisted of a top chamber and a base, with the base fixed in the soil at the sampling point and the top chamber measuring 320 mm × 600 mm. During sampling, the top chamber was embedded into the groove of the base and sealed with water. Sampling was conducted on clear days in mid-June, mid-July, mid-August, and mid-September, with adjustments of 1-3 days for special weather conditions. Sampling time was between 09:00 and 12:00. After sealing the top chamber, gas samples were collected three times at 0 min, 15 min, and 30 min (starting from the sealing moment) using a 100 mL medical syringe with a three-way valve. Each collection was 60 mL, stored in aluminum foil gas bags, and analyzed within one week. An Agilent 4890D gas chromatograph was used to measure CO_2 and CH_4 concentrations in the samples. The gas flux was calculated using the following formula:

$$F = \rho \times \frac{273}{273 + T} \times h \times \frac{C_t - C_0}{t}$$

where F represents the gas flux ($\mathrm{mg \cdot m^{-2} \cdot h^{-1}}$); ρ represents the gas density under standard conditions ($\mathrm{kg \cdot m^{-3}}$); h represents the static dark chamber height (m); C_t and C_0 represent the gas volume fraction concentrations in the chamber at time t and at the start, respectively ($\mathrm{L \cdot L^{-1}}$); T represents the average temperature inside the chamber during sampling (°C); and t represents the time during gas sampling (h). Cumulative emission or absorption of gases was calculated by multiplying gas flux by monitoring duration.

1.5 Data analysis

Data processing and analysis were performed using Excel and SPSS 27.0 software, with figures created using ArcMap 10.8 and Origin 2021. One-way ANOVA and least significant difference multiple comparisons were used to test the significance of differences in various indicators among different grassland wind erosion pit development stages ($\alpha < 0.05$). Pearson correlation analysis was used to analyze correlations between plant carbon pools, soil carbon pools, and environmental factors, with principal component analysis used to determine the influence degree of each factor.

2.1 Effects of wind erosion pit development on plant biomass and carbon pool

Wind erosion pit development significantly reduced total biomass, aboveground biomass, belowground biomass, and litter biomass at all stages compared with natural grassland. Specifically, these indicators decreased by 82.10%, 82.41%, 95.16%, and 84.44%, respectively, in the wind-eroded bare land stage; by 97.09%, 97.71%, 64.91%, and 97.21%, respectively, in the active blowout stage; and by 66.57%, 66.58%, 71.89%, and 80.45%, respectively, in the extinct blowout stage. Compared with natural grassland, the average reduction in each biomass indicator was 82.35%, 96.79%, and 67.49% in the wind-eroded bare land, active blowout, and extinct blowout stages, respectively, with the most pronounced effects observed in the active blowout stage [Figure 2: see original paper].

Similarly, wind erosion pit development significantly reduced aboveground carbon storage, belowground carbon storage, litter carbon storage, and total carbon storage at all stages. These indicators decreased by 78.29%, 79.69%, 61.70%, and 75.71%, respectively, in the wind-eroded bare land stage; by 96.76%, 94.24%, 94.47%, and 95.48%, respectively, in the active blowout stage; and by 66.62%, 58.90%, 36.57%, and 57.21%, respectively, in the extinct blowout stage [Figure 3: see original paper]. Additionally, during wind erosion pit development, organic carbon content in aboveground plant parts showed a significant increasing trend, while organic carbon content in belowground roots and litter showed no significant changes.

2.2 Effects of wind erosion pit development on soil properties and carbon pool

During wind erosion pit development, soil water content, porosity, field capacity, silt content, and clay content decreased significantly, while pH, bulk density, and sand content increased significantly . Soil carbon content also decreased significantly [Figure 4: see original paper]. Compared with natural grassland, soil total carbon storage decreased by 18.68%, 52.24%, and 22.59% in the wind-eroded bare land, active blowout, and extinct blowout stages, respectively. During the active blowout stage, soil organic carbon content decreased by an average of 63.53%, with surface soil (0–20 cm) losses reaching 69.51%. Microbial biomass carbon content decreased by an average of 74.58%, with surface soil (0–20 cm) losses reaching 76.80%. Soil inorganic carbon decreased by an average of 61.08%, with middle-layer soil (20–40 cm) losses reaching 68.43%. Total carbon decreased by an average of 74.58%, with middle-layer soil (20–40 cm) losses reaching 31.04%. These results indicate that wind erosion pit development significantly reduced the soil carbon pool ($P < 0.05$).

2.3 Effects of wind erosion pit development on soil carbon emissions

During the growing season, CO_2 emission fluxes from natural grassland soil were significantly higher than those at all stages of wind erosion pit development, indicating that wind erosion pit development significantly interfered with soil CO_2 flux ($P < 0.05$). During wind erosion pit development, the grassland ecosystem showed CH_4 absorption status [Figure 5: see original paper]. The monthly average absorption flux from June to September decreased in the following order: natural grassland stage ($0.103\ g \cdot m^{-2} \cdot h^{-1}$) > extinct blowout stage ($0.032\ \mathrm{g \cdot m^{-2} \cdot h^{-1}}$) > wind-eroded bare land stage ($0.288\ \mathrm{g \cdot m^{-2} \cdot h^{-1}}$) > active blowout stage ($0.116\ \mathrm{g \cdot m^{-2} \cdot h^{-1}}$). Cumulative CH_4 absorption was 0.288, 0.116, 0.032, and 0.103 $\mathrm{g \cdot m^{-2}}$ in the natural grassland, wind-eroded bare land, active blowout, and extinct blowout stages, respectively. Compared with natural grassland, CH_4 absorption in the active blowout stage decreased by 88.89%, and the soil even released CH_4 during May-June. These results demonstrate that wind erosion pit development altered the spatiotemporal pattern of soil carbon-containing greenhouse gas fluxes.

2.4 Relationships between plant-soil carbon pools and environmental responses

Soil organic carbon content showed a significant positive correlation with soil porosity and field capacity, and a highly significant negative correlation with soil bulk density. Soil inorganic carbon content showed a significant positive correlation with soil porosity and a significant negative correlation with soil bulk density. Soil microbial biomass carbon content showed a highly significant positive correlation with soil water content. Soil total carbon content showed a highly significant positive correlation with soil porosity and a highly significant negative correlation with soil bulk density. Soil water content showed a significant negative correlation with soil sand content and a significant positive correlation with soil clay content [Figure 6: see original paper]. Soil physicochemical properties were significantly correlated with various soil carbon content indicators, which in turn showed positive correlations with plant carbon storage indicators, indicating a close relationship between soil property changes and plant carbon storage.

Principal component analysis [Figure 7: see original paper] showed that the first two components explained 91.4% of the variance, effectively reflecting the influence of environmental factors on the plant-soil carbon pool. The first component explained 84.7% of the variance and represented the most significant factor affecting the plant-soil carbon pool during wind erosion pit development. Soil bulk density (0.98) and soil porosity (0.97) had large absolute values in the first component, indicating that changes in soil pore structure were the primary driving factor causing changes in the plant-soil carbon pool. The second component explained 6.7% of the variance, with soil sand content (0.62) having the largest absolute value, indicating that soil texture change was a secondary driving factor. Comprehensive analysis revealed that significant changes in soil bulk density, porosity, and silt content caused soil structure destruction under wind erosion pit development, thereby losing physical protection for organic carbon and representing the main reason for reduced ecosystem carbon sequestration capacity.

3.1 Effects of wind erosion pit development on soil properties

Unreasonable human activities cause grassland degradation and accelerate wind erosion pit development. This study found that soil bulk density increased and porosity decreased within wind erosion pits, as strong winds removed fine particles, destroyed soil structure, and deteriorated aeration. Additionally, soil water content and field capacity decreased significantly. Similar phenomena were observed in studies of wind erosion pits in Hulun Buir. Wind erosion pit development caused substantial water loss, forming dry zones, while soil sand content increased significantly and soil gradually coarsened. Research indicates that sandy grassland soils have a colloidal surface layer overlying a looser sand layer. As erosion intensified, the sand layer was gradually hollowed out, eventually causing surface collapse and forming surface breaches under gravity. Once surface breaches appeared, fine silt and clay particles were severely lost, soil particles within pits became coarser, and sandification intensified. Soil pH showed an alkaline trend during wind erosion pit development, indicating secondary salinization effects. Plant roots release CO_2 through respiration, forming acid radicals that regulate soil pH. However, in wind erosion pits, deteriorated moisture conditions increased evaporation intensity and salt accumulation, creating high-salt, water-deficient environments that drastically reduced plant biomass and decreased acid production, weakening timely and effective pH regulation.

3.2 Effects of wind erosion pit development on plant carbon pool

The plant carbon pool is crucial in grassland ecosystem carbon cycling, and as producers, plant species composition and growth characteristics are highly sensitive to environmental changes. This study found that wind erosion pit development did not significantly change organic carbon content in plant roots and litter, but caused severe plant carbon pool losses. This occurred because strong winds removed surface soil, causing sandification and vegetation destruction that reduced biomass. Litter biomass decreased because deteriorated soil structure inhibited plant growth, and surface vegetation loss prevented plant residues from accumulating. Belowground biomass also decreased significantly due to root exposure, physical damage, and water loss caused by wind erosion. Additionally, wind erosion pit development affected the redistribution of energy and materials such as light, water, temperature, and airflow, causing microhabitat changes that further contributed to plant carbon pool losses. In summary, while plant organic carbon content did not change significantly, the substantial reduction in plant biomass was the main cause of plant carbon pool changes. Habitat deterioration was the primary driver of reduced plant biomass accumulation, and large losses in the plant carbon pool directly affected the carbon sequestration capacity and potential of the entire grassland ecosystem.

3.3 Effects of wind erosion pit development on soil carbon pool and carbon fluxes

Plant carbon pool changes affect ecosystem carbon input and alter soil carbon dynamics. Soil carbon pool dynamics are related to plant carbon pool input and belowground carbon output. Wind erosion pit development caused severe soil carbon pool losses, with the most direct driver being the reduction in plant carbon pool input. The decrease in soil organic carbon was mainly attributed to sparse vegetation caused by strong wind erosion. Without surface vegetation protection, surface organic matter was lost, while reduced soil water content and fine particle content prevented the formation of aggregate structures to retain nutrients, ultimately causing organic carbon loss. Wind erosion pit development also reduced soil microbial respiration, primarily due to decreased microbial quantity and activity. The unstable soil environment could not provide effective carriers and nutrient sources for microbial proliferation. Strong winds removed surface organic matter and nutrients, leaving microorganisms without sufficient nutrients for normal metabolism and respiration. When surface vegetation was lacking, solar radiation reached the soil surface directly, and under the disturbance of solar radiation and wind erosion, soil water and gas exchange were blocked, causing soil temperature and moisture imbalances that inhibited microbial activity and weakened soil microbial respiration.

Wind erosion pit development caused not only severe soil organic carbon loss but also substantial soil inorganic carbon reduction. Soil inorganic carbon sources include atmospheric deposition, microbial decomposition of soil organic matter, and carbonate formation from carbon-containing ions combining with cations in soil solution. Wind erosion destroyed surface vegetation and soil, reducing soil organic carbon and weakening microbial activity, thereby inhibiting mineralization of soil organic carbon to inorganic carbon. Simultaneously, wind erosion significantly reduced soil water content and porosity, hindering carbonate ion formation and diffusion and preventing carbon-containing ions in soil solution from effectively combining with cations, further reducing carbonate mineral formation. Soil microbial biomass carbon content also decreased because wind erosion pit development damaged the soil system, causing soil fertility decline that inhibited microbial growth.

Changes in soil carbon-containing gas fluxes represent gas exchange between the soil carbon pool and atmosphere and constitute an important factor maintaining soil carbon pool stability. Soil CO_2 emissions occur through two pathways: plant root respiration and soil microbial respiration. This study found that reduced soil carbon exchange in wind erosion pits was mainly caused by structural damage from wind erosion, leading to decreased plant root biomass and weakened microbial activity. During wind erosion, external forces caused physical damage and even death to plant roots, while soil structure destruction weakened the ability to retain moisture and transport oxygen. Good soil aeration enhances oxygen entry into soil, but when oxygen supply decreases, plants initiate stress responses that inhibit metabolic processes including respiration, reducing root CO_2 emissions. Wind erosion pit development reduces grassland ecosystem CH_4 absorption and may even cause CH_4 release. CH_4 oxidation is the only pathway for CH_4 to be collected by terrestrial ecosystems, performed by methanotrophic bacteria. In well-aerated mineral soils, methanotrophic activity is high. Wind erosion pit development deteriorates soil aeration, which is unfavorable for aerobic methanotrophs but allows anaerobic methanogenic bacteria to grow and emit CH_4 under harsh soil conditions. CH_4 absorption and emission processes occur simultaneously, and when soil environment deteriorates, the dynamic balance between CH_4 production and consumption may be disrupted, causing grassland ecosystems that originally absorbed CH_4 to emit CH_4 after developing into wind erosion pits. In summary, when soil is damaged by wind erosion pit development, the dynamic changes in soil carbon-containing gas exchange constitute another reason for changes in the soil carbon pool.

---

4 Conclusions

(1) Plant total carbon storage significantly decreased by 75.71%, 95.48%, and 57.21% in the wind-eroded bare land, active blowout, and extinct blowout stages, respectively, indicating that the entire process severely weakened plant carbon sequestration capacity. (2) Soil total carbon storage also decreased by 18.68%, 52.24%, and 22.59% in the wind-eroded bare land, active blowout, and extinct blowout stages, respectively, further demonstrating the impact of wind erosion pit development on ecosystem carbon pools. (3) CO_2 emissions decreased by 37.17%, 60.99%, and 22.93%, while CH_4 absorption decreased by 59.72%, 88.89%, and 64.23% in the wind-eroded bare land, active blowout, and extinct blowout stages, respectively, indicating significant changes in soil carbon-containing gas fluxes during wind erosion pit development. (4) Plant biomass loss and changes in soil aeration and other structural indicators were key factors causing changes in plant-soil carbon dynamics. Therefore, targeted protection measures should be implemented for grassland wind erosion pits, with increased efforts in vegetation reconstruction and soil restructuring for ecological restoration and protection to recover carbon sequestration capacity in sandy grasslands.

References

[1] Jia Zhaojie. Effects of plant aboveground and belowground inputs on soil carbon organic pools and microorganisms[D]. Shenyang: Shenyang Agricultural University, 2023.

[2] Regnier P, Friedlingstein P, Ciais P, et al. Anthropogenic perturbation of the carbon fluxes from land to ocean[J]. Nature Geoscience, 2013, 6(8): 597-607.

[3] Wang Guocheng, Xiao Liujun, Lin Ziqi, et al. Most derived carbon inputs do not contribute to long term global soil carbon storage[J]. Scientia Sinica

(Terrae), 2023, 53(5): 1067-1082.

[4] Crowther T W, Todd Brown K E O, Rowe C W, et al. Quantifying global soil carbon losses in response to warming[J]. Nature, 2016, 540(7631): 104-108.

[5] Jackson R B, Lajtha K, Crow S E, et al. The ecology of soil carbon: Pools, vulnerabilities, and biotic and abiotic controls[J]. Annual Review of Ecology, Evolution, and Systematics, 2017, 48(1): 419-445.

[6] Wang H, Li Y Z, He Y C, et al. Grazing exclusion facilitates more rapid ecosystem carbon sequestration of degraded grasslands in humid than in arid regions[J]. Agriculture Ecosystems & Environment, 2023, 353: 108553, doi: 10.1016/j.agee.2023.108553.

[7] Guan Weitao, Zheng Zhirong, Diao Zhaoyan, et al. Stoichiometric characteristics and their storage of soil carbon, nitrogen and phosphorus in the temperate meadow steppe under different disturbance[J]. Acta Agrestia Sinica, 2022, 30(11): 2959-2966.

[8] Tanabe K. A tentative classification of sand dunes its application to dune history in the southern high plains[J]. Geographical Review of Japan, 1940, 16(9): 645-653.

[9] Bagnold R A. The physics of blown sand and desert dunes[M]. London: Mathuen & Co. Ltd, 1941: 11-40.

[10] Yan Xu, Zhang Deping, Xia Xiandong, et al. Morphology and developmental mode of blowouts in Hulun Buir sandy grassland, China[J]. Journal of Desert Research, 2009, 29(2): 212-218.

[11] Zhang Deping, Sun Hongwei, Wang Xiaoke, et al. Hulun Buir sandy grassland blowouts (Part II): Process of develpoment and landscape evolution[J]. Journal of Desert Research, 2007, 27(1): 20-24.

[12] Catto N, MacQuarrie K, Hermann M. Geomorphic response to Late Holocene climate variation and anthropogenic pressure, northeastern Prince Edward Island, Canada[J]. Quaternary International, 2002, 87(1): 101-117.

[13] Hesp P. Foredunes and blowouts: Initiation, geomorphology and dynamics[J]. Geomorphology, 2002, 48(1-3): 245-268.

[14] Jungerius P D, van der Meulen F. The development of dune blowouts, as measured with erosion pins and sequential air photos[J]. Catena, 1989, 16(4-5): 369-376.

[15] del Vecchio S, Rova S, Fantinato E, et al. Disturbance affects the contribution of coastal dune vegetation to carbon storage and carbon sequestration rate[J]. Plant Sociology, 2022, 59(1): 37-48.

[16] Zhang Deping, Feng Zongwei, Wang Xiaoke, et al. Preliminary study on aeolian erosion pits in the sandy grassland of Hulun Buir[J]. Progress in Natural Science, 2006(10): 1341-1345.

[17] Lu Rukun. Methods of soil agricultural chemical analysis[M]. Beijing: China Agricultural Science and Technology Press, 2000: 135-159.

[18] Wang H H, Shen M X, Hui D F, et al. Straw incorporation influences soil organic carbon sequestration, greenhouse gas emission, and crop yields in a Chinese rice (Oryza sativa L.) - wheat (Triticum aestivum L.) crop system[J]. Soil and Tillage Research, 2019, 195: 104377, doi: 10.1016/j.still.2019.104377.

[19] Li Yuwei, Wang Bo, Bao Yuhai, et al. Effects of the development of grassland blowouts on soil ecological stoichiometry[J]. Journal of Desert Research, 2023, 43(5): 166-175.

[20] Yuan Limin, Yang Zhiguo, Xue Bo, et al. Heterogeneity of soil moisture of blowouts in HulunBuir grassland[J]. Arid Zone Research, 2022, 39(5): 1598-1606.

[21] Grout H, Tarquis A M, Wiesner M R. Multifractal analysis of particle size distributions in soil[J]. Environmental Science & Technology, 1998, 32(9): 1176-1182.

[22] Luo Dan, Chen Jixiang, Cheng Lin, et al. Analysis of bacteria diversity in the rhizosphere soil of three main plants and its correlation with the soil physical and chemical properties in the desertification area of northern Shaanxi[J]. Journal of Arid Land Resources and Environment, 2019, 33(3): 151-157.

[23] Davidson E A, Janssens I A. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change[J]. Nature, 2006, 440(7081): 165-173.

[24] Yan Deren. Impact factors and morphological characteristics of blowouts in Hunshandake Sandland[J]. Scientia Geographica Sinica, 2016, 36(4): 637-642.

[25] Luo Z K, Feng W T, Luo Y Q, et al. Soil organic carbon dynamics jointly controlled by climate, carbon inputs, soil properties and soil carbon fractions[J]. Global Change Biology, 2017, 23(10): 4439-4453.

[26] Deng L, Shangguan Z P, Wu G L, et al. Effects of grazing exclusion on carbon sequestration in China’ s grassland[J]. Earth Science Reviews, 2017, 173: 84-95.

[27] Yan Min, Chen Yuxin, Zuo Hejun, et al. Redistribution characteristics of aeolian sand flow on different underlying surfaces at the edge of Hobq Desert and their enrichment effect on nutrients[J]. Arid Land Geography, 2023, 46(6): 889-899.

[28] He Haoyu, Liu Wei, Chang Zongqiang, et al. Effects of biological soil crust succession on soil nutrients, microbial community composition in desert regions[J]. Arid Land Geography, 2024, 47(10): 1724-1734.

[29] Larney F J, Bullock M S, Janzen H H, et al. Wind erosion effects on nutrient redistribution and soil productivity[J]. Journal of Soil and Water Conservation, 1998, 53(2): 133-140.

[30] Hanson P J, Edwards N T, Garten C T, et al. Separating root and soil microbial contributions to soil respiration: A review of methods and observations[J]. Biogeochemistry, 2000, 48: 115-146.

[31] Duan Daixiang, Wang Meiqi, Zhao Liying, et al. Wetland degradation of Tamarix chinensis induced changes in soil inorganic carbon stocks and related environmental factors in the Yellow River delta[J]. Chinese Journal of Soil Science, 2023, 54(6): 1308-1315.

[32] Wen Yiyao. Simulating the impact of soil wind erosion on soil carbon flux in Inner Mongolia shrub encroachment grasslands[D]. Nanchang: Jiangxi Normal University, 2024.

[33] Beltrami H. On the relationship between ground temperature histories and meteorological records: A report on the Pomquet station[J]. Global and Planetary Change, 2001, 29(3-4): 327-348.

[34] MacDonald J A, Skiba U, Sheppard L J, et al. The effect of nitrogen deposition and seasonal variability on methane oxidation and nitrous oxide emission rates in an upland spruce plantation and moorland[J]. Atmospheric Environment, 1997, 31(22): 3693-3704.

[35] Zheng Xiaping, Wu Fuzhong, Wu Qiuxia, et al. The effects of litter input on CH_4 uptake in forest soils[J]. Chinese Journal of Ecology, 2024, 43(11): 3309-3316.

[36] Tong Chuan, Luo Min, Tan Ji. Complexity of effects of nitrogen input on methane metabolism in wetlands and mechanism analysis[J]. Acta Ecologica Sinica, 2024, 44(4): 1324-1335.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.