Postprint: Heterogeneous Effects of Wind Erosion Pits on Soil Moisture in the Hulunbuir Grassland

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Abstract

Wind erosion pits are a common type of wind erosion landform in sandy grasslands, representing an important manifestation of grassland desertification that exerts strong destructive effects on grassland vegetation. This study selected wind erosion pits in the Hulunbuir Grassland at an active development stage as research objects, with surrounding grasslands serving as controls, to investigate soil water content at different positions and depths inside and outside the wind erosion pits. The results showed: (1) Wind erosion pits create a "breach" effect on grassland soil moisture, causing a significant reduction in soil water content in surrounding grasslands within a range of nearly 20 m, and forming a "dry belt" within the 0–3 m range at the pit edge, where soil water content is 45.15% lower than the control; (2) Soil water content inside the sand pit is 44.44% lower than the control, but soil water content in the downwind sand accumulation area of the pit shows no significant difference from the control; (3) Soil water content at different depths in both the sand pit and sand accumulation area of wind erosion pits exhibits high heterogeneity, with the coefficient of variation (CV) reaching over 50%, and as soil depth increases, soil water content shows a trend of first increasing and then decreasing; (4) After the rainy season, the sand accumulation area of wind erosion pits demonstrates a certain "water storage" effect, whereas the sand pit and edge areas exhibit severe "water loss" effects, with soils in an extremely dry state, providing conditions for wind erosion expansion of the pit.

Full Text

Heterogeneity of Soil Moisture of Blowouts in HulunBuir Grassland

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[Figure 5: see original paper]

Abstract: Blowouts are a common wind erosion landform in sandy grasslands and represent an important manifestation of grassland desertification, causing severe damage to grassland vegetation. This study selected blowouts in the active development stage in HulunBuir grassland as research objects, with surrounding grassland serving as the control, to investigate soil water content at different locations and depths both inside and outside the blowouts. The results indicate: (1) Blowouts create a "crevasse effect" on grassland soil moisture, causing a significant reduction in soil water content in the surrounding grassland within nearly 20 m. A "dry zone" formed within 0–3 m of the blowout edge, where soil water content was 45.15% lower than the control. (2) Soil water content in the blowout pit was 44.44% lower than the control, while no significant difference was observed between the downwind sand accumulation area and the control. (3) Soil water content showed substantial heterogeneity across different depths in the blowout pit and sand accumulation area, with coefficient of variation (Cv) exceeding 50%. As soil depth increased, soil water content first increased and then decreased. (4) After the rainy season, the sand accumulation area of blowouts demonstrated certain "water storage" capacity, while the blowout pit and edge zone exhibited severe "water loss" effects, with soil in an extremely dry state that provides conditions for wind erosion expansion and morphological development of blowouts.

Keywords: blowout; soil erosion; soil water content; spatial scale; HulunBuir grassland

Blowouts are an important aeolian landform type in sandy coasts, sandy grasslands, and sandy lands [1–3], representing a primary type and manifestation of vegetation degradation and land desertification [4–6]. Blowouts can be divided into coastal sandy blowouts and inland blowouts, with relevant research in China mainly focusing on inland blowouts. Inland blowouts can be further classified as flat grassland blowouts [7-8] and fixed dune blowouts [9-10]. Fixed dune blowouts represent reactivation of stabilized sandy land and feature greater undulation and more complex terrain compared to grassland blowouts. Grassland blowouts represent the initial stage of active dune formation, where the development and superposition of adjacent multiple blowouts promote the formation of continuous sand belts in accumulation areas [11-12], severely reducing grassland landscape stability and productivity and leading to grassland desertification.

The occurrence and development of blowouts destroy grassland soil structure, bury grassland with underlying sandy material, and cause accelerated evolution from grassland landscape to sandy landscape through the dual effects of wind erosion and sand burial and the expansion and superposition of multiple adjacent blowouts [13-14]. Based on differences in blowout size, shape, and vegetation conditions, their development process can be divided into evolution stages including bare sand patches, active development, stabilization (extinction), and reactivation [15-17], among which the active development stage exhibits the strongest erosion-accumulation dynamics.

Blowouts are a combination of erosion pits and sand accumulation areas on a grassland matrix, presenting geomorphological shapes such as troughs, saucers, and ovals [4,11,14]. Different blowout shapes affect internal aeolian flow patterns, representing the main factor influencing blowout erosion-accumulation patterns and reflecting the coupling relationship between blowout morphology and aeolian dynamics. Numerous scholars have conducted systematic studies on blowout formation processes [7-8,10-11,18-19], morphological patterns [4,11,14], aeolian movement patterns [7,20-21], and control technologies [22-23] through field observations, wind tunnel experiments, and numerical simulations. However, research on blowout soil properties is relatively scarce, focusing primarily on soil particle size [16,27-30].

Soil moisture is a key factor affecting soil wind erosion processes [31-32]; lower moisture content makes sand particles more mobile and susceptible to wind erosion. What connections exist between blowout formation and development processes and soil moisture changes? What impacts do blowouts have on grassland soil moisture? Currently, research on blowout soil moisture is relatively lacking, leading to unclear understanding of the positive and negative effects of blowouts on grassland soil moisture. Therefore, this study selected typical blowouts in the active development stage in HulunBuir grassland as research objects, divided them into component parts based on geomorphological characteristics, and measured soil water content in different parts and at different distances from blowouts in the 0-100 cm soil layer, aiming to clarify the spatial distribution characteristics of blowout soil moisture and its impact on grassland soil moisture, providing a basis for studying blowout development driving forces and wind erosion control.

1.1 Study Area Overview

The HulunBuir Sandy Land (117°12 -121°10 E, 47°20 -49°50 N) is located in the hinterland of HulunBuir grassland, mainly composed of four sand belts: the sand belt along the Hailar River coast dominated by fixed and semi-fixed dunes with some active dunes and blowouts; the ancient river channel distribution sand belt in the middle Su Min Nuo Ri and Gun Nuo Er areas dominated by barchan dune chains; the southern sand belt divided by Huhe Nuo Er into east and west parts dominated by dune chains; and the sand belt along the Yimin River in the southeast with large numbers of active dunes, where blowouts are relatively newly formed [24].

HulunBuir Sandy Land is situated in HulunBuir grassland with a temperate semi-arid grassland climate. The annual dryness index shows an increasing trend, indicating a predominantly arid climate [25]. The annual average temperature ranges from -2.5 to 0°C, with annual accumulated temperature of 1790–2820°C ($ 10°C) and 102.4 days of growth period. Annual precipitation averages 353.7 mm, while annual potential e… s{-1}, maximum wind speed of 20 m · s{-1}, and spring average wind speed of 4 m · s^{-1}$, with $ 26 days of gale − force winds ($level 8) annually. Sandy land soils are mainly aeolian sandy soils, while grassland soils are sandy chestnut soils with calcic horizons typically at 10–30 cm depth, underlain by Hailar Formation fluvio-lacustrine sands.

The natural zonal dominant plants in HulunBuir grassland are *Leymus chinensis*, *Stipa grandis*, *Agropyron cristatum*, and *Cleistogenes squarrosa*. Dunes are mainly dominated by shrub communities of *Caragana microphylla*, *Rosa davurica*, *Artemisia desertorum*, and *Salix gordejevii*, accompanied by *Agriophyllum squarrosum*, *Corispermum candelebrum*, *Salsola collina*, and *Setaria viridis* [26]. Wild forage grasses in HulunBuir grassland can reach 426 species, with Compositae being the main component of wild forage plants [27].

1.2 Blowout Part Division

Blowouts are typical wind erosion-accumulation landforms. Based on terrain, soil type, and vegetation differences, blowouts were divided from inner to outer parts using field surveys combined with UAV image identification methods: blowout pit, edge zone, heavy sand accumulation area, light sand covering area, and grass-sand transition zone. Field investigations found that sand accumulation areas outside the pit could be divided into heavy sand accumulation area, light sand covering area, and grass-sand transition zone. The heavy sand accumulation area has virtually no vegetation growth, the light sand covering area has sporadic plant growth, and the grass-sand transition zone has abundant vegetation growth with significantly different species composition [28].

In the study area, blowouts in the activation stage [15] were selected, preferably isolated blowouts without adjacent contact or superposition. UAVs provided real-time imagery feedback at 100 m altitude above ground, combined with field surveys to determine boundaries of each blowout zone. GPS was used to collect boundary points for each blowout zone to complete zoning and area calculations, with 30 blowouts measured in total [Figure 1: see original paper].

[Figure 1: see original paper] Location and distribution characteristics of blowouts in the study area

1.3 Soil Moisture Measurement

Three independently distributed blowouts with northwest orientation were selected in the study area. Soil sampling was conducted according to blowout development direction, with three transect lines starting from inside the blowout pit to the upwind surrounding grassland at 0.1 m, 0.5 m, and 1.0 m intervals from the pit edge, with 10 sampling points per transect. Simultaneously, along three transect lines from the downwind inner edge of the blowout pit outward, sampling points were set at equal intervals, totaling 30 points. In the upwind direction of the blowout, sampling points were randomly set in unaffected grassland as control points (10 points) [Figure 2: see original paper].

[Figure 2: see original paper] Sampling locations and local geomorphic features of blowout

In mid-September, soil samples were collected at each sampling point using a soil auger at 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm depths, with three replicates per sampling point. Soil moisture was measured using the oven-drying method. The sampling period was at the end of the plant growing season when summer rainfall recharge was essentially complete and the wind season was beginning. Soil moisture characteristics during this period could reflect the recovery status of blowout soil moisture after the rainy season and also indicate the wind erosion potential of blowout surface soil during the wind season, demonstrating blowout moisture heterogeneity to some extent.

1.4 Data Analysis

Excel 2007 was used for data processing and charting, SAS 9.2 for variance analysis and other statistical analyses, and Surfer 8.8 for drawing contour maps.

2 Results

2.1 Differentiation Characteristics of Typical Blowout Parts

Blowouts are mostly composed of depression pits and sand material accumulation areas [4]. Blowouts in active and fixed development stages can be divided into five typical parts with significant differentiation among parts. Based on terrain characteristics, soil types, and vegetation cover, blowouts were divided from inner to outer parts into blowout pit, edge zone, heavy sand accumulation area, light sand covering area, and grass-sand transition zone, with significant differences in area among parts. The maximum pit area accounted for only 9.32% of total blowout area, while the grass-sand transition area could reach 52.18% of total blowout area. The sand accumulation area formed by blowouts accounted for 88.11% of total blowout area, meaning the vast majority of blowout areas were in a state of sand material accumulation [TABLE:1, FIGURE:3].

Morphological parameters of blowouts

Note: Different uppercase letters indicate significant differences in area ratio among different blowout parts at $P < 0.05$ level.

[Figure 3: see original paper] Percentage of the area of each typical part in the total area of blowouts

2.2 Soil Moisture Characteristics of Different Blowout Parts

Figure 4 shows the average soil moisture content in 0–100 cm soil layers of different parts of three blowouts. Overall comparison shows that soil moisture in the five typical parts of blowouts was relatively low, all below 6.67%, decreasing by 45.15%, 44.44%, and 36.72% compared with control grassland (10.5%). Soil moisture in the blowout pit was significantly lower than in sand accumulation areas, reaching 44.44%. Although the sand accumulation area was formed by dry sand material accumulation, its soil moisture was close to that of non-desertified grassland, indicating that after the rainy season, soil moisture in this area was replenished to some extent. Aeolian sandy soil allowed rapid infiltration of excess water, but the buried original grassland soil layer underneath blocked and effectively retained the infiltrated water.

Note: Different uppercase letters indicate significant differences in soil moisture content among different blowout parts at $P < 0.05$ level.

[Figure 4: see original paper] Soil moisture content of blowouts and external grassland

2.3 Impact of Blowouts on Surrounding Grassland Soil Moisture

Blowouts not only affect soil moisture within their own range but also influence soil moisture in surrounding grassland laterally. During vertical changes in soil moisture, blowouts significantly affected surrounding grassland soil moisture: the closer to the blowout, the lower the soil moisture; the farther away, the gradually increasing soil moisture. Within the inner edge of the edge zone at 0–1 m, soil moisture reduction was greatest, with this area in the 0-3 m range. Next was the 1–3 m range, which was in the sand covering area (approximately 3–10 m). When soil moisture at 10–30 m was in the grass-sand transition zone (1–20 m), and at >35 m it was in grassland without sand accumulation, soil moisture gradually approached that of the control [Figure 5: see original paper].

Note: Different uppercase letters indicate significant differences in soil moisture content changes at different distances outward from blowout edges at $P < 0.05$ level.

[Figure 5: see original paper] Variation of soil water content at different distances outward from the edge of blowouts

2.4 Soil Moisture Change Characteristics in Blowout Sand Accumulation Areas

From the downwind inner edge of the blowout pit to the external grassland, the area can be divided into heavy sand accumulation area, light sand covering area, and grass-sand transition zone. Figure 6 shows that from the sand pit inner edge to 2.3 m distance, shallow soil at about 0–0.3 m depth had soil moisture below 6.5%–6.67%, with an average of 6.67%. The 0–0.3 m area at the pit inner side wall and the 0.4 m area far from the pit had soil moisture of 3.5%–5.5%, with significant differences between these areas. The surface and side wall soils in the 0–0.3 m area were all chestnut soil, with severe water loss, and lateral capillary action caused deep water loss that could affect the area 0.4 m from the side wall. This area remained dry for long periods, making underlying layers susceptible to wind erosion and causing upper side wall collapse. The 0.4–2.3 m area had relatively high soil moisture above 10.5%, mainly distributed below the 40–60 cm soil layer. As distance from the blowout pit increased, the dry soil layer became shallower and thinner, further demonstrating that moderate sand covering helps increase grassland soil moisture. The sand layer allows effective infiltration of precipitation while easily forming a dry sand layer that inhibits water loss.

[Figure 6: see original paper] Soil moisture contour map of different distances outward from the edge of blowouts

2.5 Soil Moisture Variation with Soil Depth

Figure 7 shows that in the five typical parts of blowouts, except for the edge zone, the other four parts all showed a trend of soil moisture first increasing then decreasing with soil depth. Soil moisture in 0–10 cm layers of the blowout pit, heavy sand accumulation area, light sand covering area, and grass-sand transition zone was all below 6.67%. As soil depth gradually increased, soil moisture in these four areas first increased then decreased, with higher water content in 40–80 cm layers, significantly different from 0–10 cm layers. Although vegetation grew in the grass-sand transition zone, its soil moisture variation trend in each layer showed no significant difference from the heavy sand accumulation area and light sand covering area, indicating that residual vegetation did not significantly affect deep soil moisture. The blowout pit soil moisture also showed an increasing then decreasing trend with soil depth, mainly because pit soil consists of Hailar Formation loose sand layers. Long-term wind erosion sorting caused severe surface soil particle coarsening, greatly reducing soil water-holding capacity, with soil moisture throughout the layer below 4.06%. The edge zone had severe surface erosion, with the entire tested soil layer being original soil layer with relatively small structural changes. Its 40–80 cm soil layer moisture (2.57%) was significantly higher than other parts, but the edge zone accounted for the smallest proportion of total blowout area (9.32%). However, this part is the starting point for blowout lateral expansion to grassland and also constrains longitudinal pit development. Soil moisture in this part was the driest compared with other parts at only 54.86%, and low moisture content increases soil erodibility [32], indicating high wind erosion risk at this stage.

[Figure 7: see original paper] Soil moisture content in typical sections of blowouts

3 Discussion

During blowout formation and development, the original zonal soil structure of grassland is destroyed. The depression pit loses chestnut soil layer protection, intensifying wind erosion subsidence and edge expansion. Grassland vegetation at the pit edge degrades, parent soil becomes exposed, edge collapse and abrasion occur frequently, and sand material continuously accumulates downwind, forming obvious sand ridges at higher elevations that gradually advance backward, burying large areas of grassland and forming light sand covering areas. Meanwhile, sand material entering the air forms sand covering in farther grassland due to terrain alleviation, creating grass-sand transition areas.

The blowouts studied represent the most active expansion stage [15], with wind erosion remnant hill traces in the pit, obvious sand ripples, thick surface coarse sand particles, and scattered psammophyte plants at the lowest points. The edge zone is located at the pit edge area with severe collapse and abrasion. Uneven soil blocks scattered on the inner side slope of the pit [11] cause upper soil mass collapse due to bottom wind erosion at the side wall. At the top of the blowout edge, the surface chestnut soil layer is exposed with sparse vegetation and significant abrasion traces. The sand accumulation area is divided into heavy sand accumulation area, light sand covering area, and grass-sand transition zone according to accumulation degree and vegetation coverage. The heavy sand accumulation area is mainly distributed downwind and on both sides of the blowout, with virtually no plant growth. Generally, the upwind edge of the pit has no heavy sand accumulation or minimal area. The light sand covering area has relatively small sand accumulation thickness, with plants appearing but poor growth and low coverage. Vegetation distribution shows certain patterns outward from the boundary with the heavy sand accumulation area. The grass-sand transition zone has open and flat terrain with obvious sand covering but generally <12–15 cm thickness. This area grows original grassland plants with higher species richness than surrounding grassland [28], but plant growth is weakened and grassland remains threatened by sand burial.

Soil moisture is directly affected by climate, vegetation, soil type, landform, terrain, and human activities, while vegetation is the direct factor affecting shallow soil moisture variation in grassland. Vigorous vegetation growth inevitably leads to developed root systems and enhanced soil water utilization, which can slow soil water movement and enhance soil water storage to some extent [39]. Blowout formation causes loss of nutrient soil and exposure of aeolian sandy soil, directly leading to grassland vegetation disappearance. Large-area sand burial also causes degradation of larger grassland areas. As sand burial thickness thins, small community dominant species show zonal replacement distribution [11]. Vegetation disappearance reduces soil water consumption but also loses root system water storage function.

This study found that blowout development caused substantial grassland soil moisture loss, creating a significant "crevasse effect." Blowouts affected soil moisture in upwind and lateral grassland, with influence extending to the grass-sand transition zone, at least 20 m from the pit edge. Simultaneously, dry sand material from wind erosion-accumulation processes was also dry in heavy and light sand accumulation areas. Dry sand material reversely absorbed water from buried original soil, and this area had virtually no vegetation growth. This dual superposition effect was the main reason for differences from surrounding grassland soil moisture. In the grass-sand transition zone, vegetation quantity gradually increased, aeolian sand activity gradually disappeared, and soil moisture change gradually became consistent with surrounding grassland.

Blowout different parts have different aeolian processes such as wind erosion and sand burial, leading to ecological environments completely different from original grassland. Under comprehensive effects of many factors, moisture heterogeneity exists in typical blowout parts. Further analysis shows that blowouts form large areas of quicksand, with bare sand surfaces replacing vegetation cover, reducing vegetation water consumption and greatly decreasing surface runoff generation. Dry sand layers effectively lock deep water. Under effective rainfall recharge, could blowouts have positive effects on deep grassland water increase? This study only investigated shallow soil moisture, and future research should expand soil depth scale to explore the relationship between blowouts and grassland soil moisture.

4 Conclusions

(1) Blowouts in sandy grassland in the active development stage show significant wind erosion-accumulation landform differentiation and can be divided into five typical parts: blowout pit, edge zone, heavy sand accumulation area, light sand covering area, and grass-sand transition zone. The sand accumulation area formed by blowouts accounts for 88.11% of total blowout area, with grass-sand transition area reaching 52.18% and maximum pit cross-section area accounting for only 9.32% of total area.

(2) Soil moisture in blowout pit and edge zone was significantly lower than control grassland, decreasing by 45.15% and 44.44% respectively. Soil moisture reduction in heavy sand accumulation area, light sand covering area, and grass-sand transition zone was not significant, but soil moisture variation across soil layers was large ($Cv > 50\%$), with edge zone Cv at 35.86% and pit Cv at 22.94%, showing no significant difference from control grassland (19.14%).

(3) Blowouts produced a significant "crevasse effect" on grassland, significantly affecting surrounding grassland soil moisture and forming a 0–3 m wide "dry zone" in the edge area, with soil moisture 45.15% lower than the control. As distance from the blowout edge increased, the degree of soil moisture reduction weakened, with significant influence extending to 20 m from the edge.

(4) After rainy season precipitation recharge, blowout sand accumulation areas could realize certain "water storage" effects, most significantly in grass-sand transition zone and light sand covering area. The blowout pit and edge zone had severe "water loss" effects, with soil in a dry state that provides conditions for wind erosion expansion and morphological development of blowouts during winter and spring.

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