Material Redistribution by Aeolian Sand Flow and Nutrient Element Enrichment on Different Underlying Surfaces at the Edge of the Kubuqi Desert: A Postprint

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Abstract

This study investigated five underlying surfaces in the Kubuqi Desert—mobile sand dunes, sand-fixing vegetation belts, windbreak and sand-blocking forests, farmland shelterbelts, and farmland—using field observation and laboratory analysis methods to analyze the particle size and elemental characteristics of surface sediments and those in aeolian sand flow at 0~100 cm height. The results showed that: (1) The surface roughness of farmland and vegetated surfaces increased significantly compared with mobile sand dunes, wind speed at 10 cm height decreased by more than 18%, and total sediment transport rate decreased by an average of 85.6%. (2) Significant differences were observed in the contents of Cu, Fe, Mn, and Zn among sand particles of different sizes; Cu and Zn contents were highest in silt, Mn content was highest in very fine sand, and Fe content was highest in fine sand. (3) Under the redistribution of materials in aeolian sand flow, the contents of silt and very fine sand increased with height, with an average increase of approximately 14 times compared with the surface; accordingly, Cu, Zn, and Mn contents increased. The content of fine sand in aeolian sand flow first increased and then decreased with height, and Fe content also showed a trend of first increasing and then decreasing, which was closely related to the elemental contents in the original surface and the characteristics of elemental contents in surface sediments of different particle sizes.

Full Text

Redistribution Characteristics of Aeolian Sand Flow on Different Underlying Surfaces at the Edge of Hobq Desert and Their Enrichment Effect on Nutrients

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Abstract

This study investigated the particle size distribution and elemental characteristics of sediments from the surface and 0–100 cm aeolian sand flow across five underlying surfaces in the Hobq Desert: mobile sand dunes, sand-stabilizing grass belts, windbreak and sand-fixing forests, farmland shelterbelts, and farmland. Through field observations and laboratory analyses, the results revealed: (1) The surface roughness of farmland and vegetation-covered surfaces increased significantly compared to mobile sand dunes, with wind speed at 10 cm height decreasing by more than 18% and total sand transport decreasing by an average of 85.6%. (2) The contents of Cu, Fe, Mn, and Zn varied markedly among different sand particle sizes, with Cu and Zn being highest in silt, Mn highest in very fine sand, and Fe highest in fine sand. (3) Under the material redistribution of aeolian sand flow, the contents of silt and very fine sand increased with height, averaging approximately 14 times higher than surface levels, accompanied by corresponding increases in Cu, Zn, and Mn contents. Fine sand content in aeolian sand flow first increased then decreased with height, while Fe content showed a similar trend, closely related to the elemental composition of the original surface and the size-dependent elemental characteristics of surface sediments.

Keywords: aeolian sand flow; particle size composition; element migration; Hobq Desert

Introduction

Trace elements such as Cu, Fe, Mn, and Zn are widely distributed in nature but occur at extremely low concentrations in soils, primarily existing as oxide-bound, exchangeable, organically-bound, carbonate-bound, and residual fractions. Although soil nutrient element contents are very low, comprising only a small fraction of plant dry weight, they play indispensable roles in plant growth. Cu enhances plant cold and drought resistance and participates in photosynthesis; Fe is essential for chlorophyll synthesis and important for both photosynthesis and respiration; Mn is involved in protein and inorganic acid metabolism and crucial for chlorophyll formation and carbohydrate accumulation and transport; Zn participates in auxin synthesis, promoting plant growth and seed development. Soil nutrient content variations are mainly influenced by natural factors and human activities, with the latter including cultivation, fertilization, and mining activities. Natural factors primarily derive from soil parent material, where differences in weathered mineral content across different soil textures also affect element concentrations.

Aeolian sand flow is a moving airflow formed by the interaction between wind and sandy land surfaces. Under the deflation and abrasion of aeolian sand flow, soil parent material is stripped, sorted, transported, and deposited, representing an important geophysical process in the formation of wind erosion landforms. Soil wind erosion not only causes land degradation in arid and semi-arid regions but also constitutes the primary cause of desertification and dust storm disasters. Previous studies have demonstrated that surface vegetation can effectively increase surface roughness and reduce wind velocity, thereby mitigating surface wind erosion and reducing the loss of fine particulate matter and nutrient elements from surface soils. Vegetation effects on wind erosion mainly manifest through changes in surface erosion rates, with the degree of influence depending primarily on vegetation coverage, height, and density. In recent years, domestic and international scholars have conducted extensive research on aeolian sand flow structure, grain size characteristics, erosion rates, and surface roughness variations across different underlying surfaces through field observations, wind tunnel experiments, and numerical simulations.

During wind erosion processes, fine particulate matter is lost from surface sediments and trace elements are transported accordingly. However, few studies have reported on the differential enrichment of nutrient elements across various underlying surfaces during wind erosion. Therefore, this study selected mobile sand dunes, sand-stabilizing grass belts, windbreak and sand-fixing forests, farmland shelterbelts, and farmland in the Hobq Desert as research objects. Surface soil samples and aeolian sand flow were collected and measured to analyze near-surface wind-sand activity, grain size characteristics of surface sediments and aeolian sand flow, and their effects on nutrient element enrichment characteristics, thereby revealing wind erosion features across different underlying surfaces in the Hobq Desert and providing theoretical support for ecological restoration and vegetation construction in sandy areas.

1.1 Study Area Overview

The study area is located in the Hobq Desert [Figure 1: see original paper], geographically positioned between 108°39 −108°41 E and 40°30 −40°31 N, within the transitional zone between arid and semi-arid regions. The area experiences dry, windy springs with scarce rainfall. The annual average temperature is 38.1°C, with extreme maximum and minimum temperatures of -30.5°C and 42°C, respectively. Precipitation is concentrated in July–September, with an annual average of 2100–2955 mm and annual average evaporation of 3000 mm. The average wind speed is 3.5 $m \cdot s^{-1}$, with maximum speeds reaching 28.7 $m \cdot s^{-1}$, and the windy season occurs from March to May. The landform consists primarily of fixed dunes, mobile and semi-fixed dunes. Soil types are predominantly aeolian sandy soils. The mobile sand dunes and farmland are unvegetated. The sand-stabilizing grass belt is dominated by *Echinops gmelinii*, *Psammochloa villosa*, and *Agriophyllum squarrosum*. The windbreak and sand-fixing forest consists mainly of *Caragana microphylla* and *Salix psammophila*, while the farmland shelterbelt is dominated by *Populus simonii*.

1.2 Methods

1.2.1 Field Experiments Experimental Period and Plot Selection: Field observations and sample collection were conducted in May 2021 at mobile sand dunes, sand-stabilizing grass belts, windbreak and sand-fixing forests, farmland shelterbelts, and farmland on the periphery of Duguitala Town in the Hobq Desert.

Wind Speed Measurement: Wind speed and direction collectors were deployed at each experimental plot, recording data every 10 minutes at heights of 10 cm, 30 cm, 50 cm, and 100 cm.

Sand Transport Measurement: A rotary sand sampler was used for sediment collection, with a total height of 100 cm and 20 collection layers, each with an inlet area of 20 mm × 50 mm. The sampler inlet always faced the incoming wind direction. Sand transport was collected simultaneously with wind speed measurements. During intense wind-sand activity, samples were collected for 10 minutes per test. After testing, samples from each layer were collected in sealed bags and transported to the laboratory. Each test was repeated three times under the same wind conditions.

Soil Sample Collection: Surface soil samples (0–2 cm) were uniformly collected from each underlying surface.

1.2.2 Laboratory Experiments Grain Size Analysis: Air-dried samples were weighed for each layer. Grain size distribution was determined using a Malvern Mastersizer 3000 laser particle size analyzer. Samples weighing $ $2.5 g were treated with hydrogen peroxide and hydrochloric acid to remove organic matter and secondary carbonate materials. For layers with insufficient sample mass (<2.5 g), samples from the same height across repeated tests were combined before analysis. Soil particle sizes were classified using the USDA system. After measurement, data from three replicate tests were averaged to reduce experimental error.

Element Determination: A pH 7.3 buffer solution was used as extractant to chelate and extract available forms of elements, which were then measured using a Hitachi ZA3000 series polarized Zeeman atomic absorption spectrophotometer.

Surface Samples: Samples were weighed and 20 mL of buffer solution was added, followed by shaking on a DT-2 oscillator for 30 minutes to fully dissolve elements in the buffer solution. After filtration, element concentrations were determined.

Aeolian Sand Flow Samples: To meet analytical requirements, samples from 0–4 cm, 4–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm, 50–70 cm, and >70 cm were mixed separately and analyzed following the same procedure as surface samples.

1.2.3 Data Processing **Surface Roughness Calculation:** The surface roughness parameter (z_0) for different underlying surfaces was calculated using the formula:

$$z_0 = \frac{z_2 - z_1}{\ln(u_1/u_2)}$$

where z_1 and z_2 are known heights, and u_1 and u_2 are wind speeds at those heights.

Element Enrichment Coefficient: The enrichment coefficient (EF) was calculated as:

$$EF = \frac{X}{Y}$$

where X is the element content in the sample and Y is the element content in surface sediments.

2 Results and Analysis

2.1 Aeolian Sand Environment Characteristics During the observation period, the study area experienced northerly winds accounting for 18.2% of the time, with an average wind speed of 11 $m \cdot s^{-1}$ and maximum wind speed of 14.3 $m \cdot s^{-1}$. Wind speeds exceeding 6.7 $m \cdot s^{-1}$ accounted for 15.0% of the total. Compared with mobile sand dunes, wind speeds over vegetated surfaces were significantly reduced, with the sand-stabilizing grass belt showing the most pronounced reduction. At 10 cm height, wind speed decreased by 74.1% compared to mobile sand dunes, while windbreak and sand-fixing forests, farmland shelterbelts, and farmland showed reductions of 18.9%, 26.1%, and 23.0%, respectively. Wind speed reduction efficiency decreased with height; at 100 cm, the reductions were 12.10%, 7.54%, 0.60%, and 5.01% for the respective surfaces. Surface roughness values were highest for the sand-stabilizing grass belt, followed by farmland, with smaller differences between farmland shelterbelts and windbreak forests.

Significant differences in sand transport rates were observed across underlying surfaces. Under an 11 $m \cdot s^{-1}$ wind condition, total sand transport was markedly reduced compared to mobile sand dunes. Total sand transport amounts were 596.1 g for mobile sand dunes, 25.3 g for sand-stabilizing grass belts, 249.6 g for windbreak and sand-fixing forests, 55.4 g for farmland shelterbelts, and 23.2 g for farmland. Sand transport rates decreased with height, following a negative power function relationship. Aeolian sand activity was concentrated in the 0–20 cm layer, accounting for 57.3%, 91.3%, 58.1%, 89.7%, and 81.7% of total transport for the respective surfaces [Figure 2: see original paper].

2.2 Surface Grain Size and Nutrient Element Characteristics Surface sediments across all underlying surfaces were dominated by fine sand, with mobile sand dunes, sand-stabilizing grass belts, windbreak and sand-fixing forests, and farmland shelterbelts showing similar mechanical compositions. Fine sand averaged 68.23%, medium sand 26.8%, and silt and very fine sand only 2.27% and 2.69%, respectively. Farmland surface sediments contained higher fine particulate content, with fine sand accounting for 50.37%, silt 23.54%, and very fine sand 22.42%, while medium sand was only 3.67% .

Nutrient element contents varied significantly across underlying surfaces and particle sizes. Cu content increased with decreasing particle size, reaching maximum values in silt. Compared to medium sand, Cu content in silt increased by 0.31 $mg \cdot kg^{-1}$ in mobile sand dunes, 0.23 $mg \cdot kg^{-1}$ in sand-stabilizing grass belts, 0.74 $mg \cdot kg^{-1}$ in windbreak and sand-fixing forests, 0.57 $mg \cdot kg^{-1}$ in farmland shelterbelts, and 0.50 $mg \cdot kg^{-1}$ in farmland. Zn content also increased with decreasing particle size, with maximum values in silt. Zn content in silt was 0.56 $mg \cdot kg^{-1}$ in mobile sand dunes, 0.48 $mg \cdot kg^{-1}$ in sand-stabilizing grass belts, 0.53 $mg \cdot kg^{-1}$ in windbreak and sand-fixing forests, 0.22 $mg \cdot kg^{-1}$ in farmland shelterbelts, and 0.90 $mg \cdot kg^{-1}$ in farmland. Fe content showed a pattern of first increasing then decreasing with decreasing particle size, with maximum values in very fine sand. Mn content was highest in fine sand across all surfaces except farmland, where it peaked in very fine sand [FIGURE:3, FIGURE:4].

2.3 Nutrient Element Content Characteristics in Different Grain Size Fractions Element contents varied markedly among different grain size fractions. With decreasing particle size, Cu and Zn contents increased, reaching maximum values in silt. Fe content first increased then decreased, peaking in very fine sand. Mn content was highest in fine sand across mobile sand dunes, sand-stabilizing grass belts, windbreak and sand-fixing forests, and farmland shelterbelts, but peaked in very fine sand in farmland [Figure 4: see original paper].

2.4 Grain Size and Nutrient Enrichment Characteristics in Aeolian Sand Flow Silt and very fine sand contents in aeolian sand flow increased with height, while medium sand content decreased. Fine sand content in farmland aeolian sand flow decreased with height, while other surfaces showed an initial increase followed by a decrease. At the surface, the ratio of silt:very fine sand:fine sand:medium sand was approximately 2:3:68:27 across all surfaces except farmland, where it was 24:22:53:0.

In the 0–30 cm layer, silt and very fine sand contents showed small increases while medium sand content decreased substantially, resulting in a slight increase in fine sand content. At 30 cm height, the ratio in farmland was 4:8:75:13, while other surfaces averaged 20:35:36:8. Above 30 cm, silt and very fine sand contents increased significantly while medium and fine sand contents decreased substantially. At the top of the aeolian sand flow layer, the average ratio for mobile sand dunes, sand-stabilizing grass belts, windbreak and sand-fixing forests, and farmland shelterbelts was 27:25:47:0, while farmland showed a ratio of 40:43:17:0 [Figure 5: see original paper].

Different nutrient elements exhibited distinct enrichment patterns in aeolian sand flow. The enrichment coefficient (EF) for Cu increased linearly with height, reaching values of 1.06, 1.08, 1.25, and 1.31 at the top of the aeolian sand flow layer for mobile sand dunes, sand-stabilizing grass belts, windbreak and sand-fixing forests, and farmland shelterbelts, respectively. Zn EF also increased linearly with height, with top-layer values of 1.25, 1.30, 1.38, and 1.42 for the respective surfaces. Fe and Mn EF values showed an initial increase followed by a decrease with height, peaking at 44.38 cm and 12.29 cm for Fe, and 29.48 cm and 38.37 cm for Mn, respectively. The peak EF values for Fe were 1.35, 1.41, 1.53, and 1.58, while for Mn they were 1.20, 1.25, 1.33, and 1.37 [Figure 6: see original paper].

2.5 Relationship Between Grain Size and Element Content in Aeolian Sand Flow Correlation analysis revealed significant relationships between element contents and grain size characteristics in aeolian sand flow . Cu content showed positive correlations with silt and very fine sand (r = 0.625–0.991) and negative correlations with fine and medium sand (r = -0.979 to -0.513) across all surfaces. Zn content exhibited similar patterns, with positive correlations with silt and very fine sand (r = 0.657–0.991) and negative correlations with fine and medium sand (r = -0.976 to -0.610). Fe content was positively correlated with fine sand in all surfaces except farmland, where it showed positive correlations with silt and very fine sand. Mn content was positively correlated with silt and very fine sand and negatively correlated with medium sand across all surfaces.

3 Discussion

Grain size is a fundamental characteristic of sediments, with composition influenced by sediment source, transport conditions, and depositional environment. Analysis of grain size characteristics is important for distinguishing depositional environments and transport mechanisms. Surface sediments in the Hobq Desert are dominated by fine sand, consistent with previous research showing that different deserts exhibit micro-scale variations in surface sediment grain size characteristics due to wind forces and vegetation cover. However, farmland surfaces, subject to long-term cultivation and fertilization, showed significantly different grain size distributions with higher silt and very fine sand contents (23.54% and 22.42%) and lower medium sand content (3.67%) compared to other surfaces.

Due to differences in surface vegetation, near-surface wind velocity profiles varied significantly among underlying surfaces. The sand-stabilizing grass belt exhibited the strongest wind speed reduction, decreasing 10 cm wind speed by 74.1% compared to mobile sand dunes. Wind speed reduction efficiency decreased with height, with reductions of 12.10%, 7.54%, 0.60%, and 5.01% at 100 cm for the respective vegetated surfaces. Surface roughness calculations ranked the surfaces from highest to lowest as: sand-stabilizing grass belt > farmland > farmland shelterbelt > windbreak and sand-fixing forest > mobile sand dunes.

These differences in wind field characteristics produced distinct aeolian sand flow structures. Previous studies have shown that sand transport rates follow a negative power function relationship with height, with aeolian sand activity concentrated below 30 cm. Our results align with these findings, showing that sand transport rates decreased with height following a negative power function, with 0–20 cm transport accounting for 57.3–91.3% of total transport across surfaces. Compared to mobile sand dunes, vegetated surfaces and farmland showed significantly increased surface roughness, reduced near-surface wind speeds, and decreased total sand transport by 58.1–96.1%.

During wind transport, differences in mass and morphology cause different grain size fractions to exhibit distinct vertical distribution patterns. Fine particles have greater initial lift velocities than coarse particles under the same aerodynamic conditions, resulting in decreased coarse particle occurrence probability with height. Consequently, silt and very fine sand percentages increased with height while medium sand content decreased substantially. In the 0–30 cm layer, silt and very fine sand showed small increases while medium sand decreased dramatically, causing a slight increase in fine sand content. Above 30 cm, silt and very fine sand increased significantly while medium and fine sand decreased. Farmland showed unique patterns due to its distinct surface grain size distribution, with high initial silt and very fine sand contents and minimal medium sand, resulting in increasing silt and very fine sand and decreasing fine sand with height.

Nutrient elements are widely present in minerals and rocks at concentrations generally below 100 $mg \cdot kg^{-1}$. Different underlying surfaces exhibit varying element content patterns due to differences in parent material, vegetation cover, and human disturbance. Previous studies have demonstrated grain-size effects on element distribution, with elements tending to enrich in finer fractions. In this study, Cu and Zn contents increased with decreasing particle size, peaking in silt. Fe content first increased then decreased with decreasing particle size, maximizing in very fine sand. Mn content was highest in fine sand across most surfaces except farmland, where it peaked in very fine sand.

The enrichment characteristics of nutrient elements in aeolian sand flow are closely related to the grain size composition of surface sediments. As wind erosion causes soil nutrient loss, different underlying surfaces interfere with wind-sand movement to varying degrees, creating differences in transport and deposition dynamics that lead to variations in aeolian sand flow structure and trace element migration and enrichment. Our correlation analysis confirmed that element contents in aeolian sand flow were significantly correlated with grain size characteristics, matching the patterns observed in surface sediments.

4 Conclusions

1. Compared to mobile sand dunes, farmland and vegetation-covered surfaces exhibited significantly increased surface roughness and substantially reduced near-surface wind speeds (by >18% at 10 cm height), with wind reduction efficiency decreasing with height. Total sand transport decreased by 58.1–96.1% across all vegetated surfaces and farmland.

2. Significant differences in Cu, Fe, Mn, and Zn contents were observed among underlying surfaces and among different grain size fractions. Cu and Zn were most abundant in silt, Mn in very fine sand, and Fe in fine sand. Under the material redistribution effects of aeolian sand flow, silt and very fine sand contents increased with height, averaging approximately 14 times higher than surface levels, accompanied by corresponding increases in Cu, Zn, and Mn contents. Medium sand content decreased with height, while fine sand content first increased then decreased. Since Fe was most abundant in fine sand, its content in aeolian sand flow also showed a pattern of initial increase followed by decrease.

3. The enrichment characteristics of nutrient elements in aeolian sand flow are closely related to the grain size-dependent element content patterns of surface sediments. Element contents in aeolian sand flow showed significant correlations with grain size characteristics, consistent with the size-dependent distribution patterns observed in surface sediments across different underlying surfaces.

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