Characteristics of Aeolian Sand Activities in Wind Erosion Desertification in the Central Grassland Region of Mongolia: A Case Study of Choir City (Postprint)

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Abstract

Mongolia is an important section of the China-Mongolia-Russia Economic Corridor, but faces serious desertification problems that pose severe threats to regional economic and social development. The central grassland region of Mongolia is the main new expansion area of desertification and is experiencing intense grassland wind erosion desertification processes. Taking Choir City, the capital of Govisümber Province, as the study area, this study investigated the basic characteristics of local wind erosion desertification, including wind dynamic conditions, sand flow transport, and other influencing factors, based on data from a self-built automatic meteorological observation station (May 2019–July 2020), a sand trap observation station (August 2019–August 2020), and local meteorological stations (1990–2018). The results show that: (1) Choir City has strong wind dynamic conditions, with an annual drift potential reaching 735.96 VU, a resultant drift potential of 428.76 VU, a resultant drift direction of SSW (195.06°), and a wind direction variability index of 0.58, belonging to a high wind energy environment with moderate variability bimodal wind regime. (2) The critical wind speed for sand initiation varies seasonally under the combined influence of soil moisture and vegetation cover, being highest in summer, lowest in winter, and moderate in spring and autumn with relatively small differences. (3) The surface has intense wind-sand activity, with an annual sand flow transport flux reaching 2.135 t · m-1 · a-1, and the Owen maximum sand transport model is suitable for simulating sand flow in this region. The research results have important reference value for sand control and ecological restoration in the central grassland region of Mongolia.

Full Text

Aeolian Sand Activity Characteristics of Wind Erosion Desertification in the Grassland Area of Central Mongolia: A Case Study of Choir City

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Abstract: Desertification is the most serious ecological and environmental problem facing the world today. Mongolia, which borders northern China, is an important country along the China-Mongolia-Russia economic corridor and a comprehensive strategic partner of China. Since 2000, Mongolia has experienced severe ecological degradation and rapid desertification development, becoming one of the four major dust storm source regions globally. Wind erosion desertification is the main form of desertification in Mongolia, seriously affecting vegetation landscapes and living environments, with the center of wind-eroded desertified land continuously expanding northward in recent years. Choir City, the capital of Gobi Sumber Province, is located in the central grassland region of Mongolia. Affected by inland arid climate and intense human activities, wind erosion desertification is extremely serious, representing a typical new expansion area of wind erosion desertification in Mongolia. Using data from a self-built automatic meteorological observation station (May 2019 to July 2020), sand collector observations (August 2019 to August 2020), and local meteorological station data, this study investigated the basic characteristics of wind erosion desertification in Choir City, including wind dynamic conditions, aeolian sand flow transport, and other influencing factors. The results show that: (1) The region has strong wind dynamic conditions for wind erosion desertification, with an annual sand drift potential of 735.96 VU, a resultant drift potential of 428.76 VU, and a resultant drift direction toward SSW (195.06°). The wind direction variability index is 0.58, indicating a high wind energy environment with moderate variability and blunted double-peak wind conditions. (2) The critical sand-driving wind speed varies seasonally under the combined influence of soil moisture and vegetation coverage, being highest in summer and lowest in winter, with spring and autumn in between and showing relatively small differences. (3) The surface experiences intense aeolian sand activity, with an annual aeolian sand flow transport flux reaching 2.135 $t \cdot m^{-1}$. The maximum sediment transport rate model is suitable for simulating aeolian sand flow in this region. These research results provide important reference value for sand control and ecological restoration in the central grassland region of Mongolia.

Keywords: wind erosion desertification; wind condition; sand-driving wind; sand drift potential; sand transport volume

1. Introduction

Desertification is the most severe ecological and environmental problem facing the world today. Mongolia, which borders northern China, is an important country along the China-Mongolia-Russia economic corridor and a crucial comprehensive strategic partner of China. Since 2000, Mongolia has experienced severe ecological degradation and rapid desertification development, becoming one of the four major global dust storm source regions. Wind erosion desertification is the primary form of desertification in Mongolia, seriously affecting vegetation landscapes and the quality of living environments. In recent years, the center of wind-eroded desertified land has continuously expanded northward. Choir City, the capital of Gobi Sumber Province, is located in the central grassland region of Mongolia. Influenced by inland arid climate and intense human activities, wind erosion desertification is extremely serious, making it a typical new expansion area of wind erosion desertification in Mongolia.

Understanding near-surface wind regime characteristics, systematically assessing wind energy environments, and mastering aeolian sand activity patterns are key components for studying the formation and evolution processes of wind erosion desertification, as well as important foundations for developing regional wind-sand disaster prevention and control systems. Numerous scholars worldwide have conducted extensive research on wind regimes and sediment transport, clarifying the relationship between wind erosion desertification and wind dynamics, revealing aeolian conditions and changes in wind-sand landforms, providing scientific basis for sand control, and guiding practical engineering construction. Dong Yuxiang studied wind erosion desertification in Tibet and concluded that wind is an important driving factor for regional wind erosion desertification. Luo Fengmin et al. conducted detailed research on sand-driving wind regimes and drift potential characteristics in the northeastern edge of the Ulan Buh Desert, providing data support for wind erosion desertification prevention and control. Zhang Zhengcai et al. studied wind energy and aeolian geomorphology in the western and southwestern Tengger Desert, providing basis for evaluating regional wind-sand activity intensity and aeolian landform evolution. Louassa studied wind regimes in the western plains of Algeria and proposed wind erosion prevention recommendations.

However, research on wind erosion desertification in the central grassland region of Mongolia remains scarce. This paper analyzes the wind dynamic conditions, aeolian sand flow transport, and related influencing factors in Choir City, located in the central grassland region of Mongolia, aiming to understand the basic characteristics of wind erosion desertification processes in this region and provide references for local wind-sand disaster prevention and ecological restoration.

2. Study Area and Methods

2.1 Study Area Overview

Mongolia is a landlocked country with precipitation gradually decreasing from north to south and average annual wind speed gradually decreasing from southeast to northwest. Choir City is the capital of Gobi Sumber Province in Mongolia, located at 108°24 E, 46°21 N, with relatively flat terrain. The vegetation landscape is grassland with coverage of 19.73%, mostly herbaceous plants with a few shrubs. Herbaceous plants are dominated by Stipa, Artemisia frigida, and Eragrostis, while shrubs are mainly Caragana. Compared with most other regions in Mongolia, this area has severe grassland degradation. From a natural regionalization perspective, Choir City is located in the mixed zone of typical grassland, dry grassland, and desert grassland [Figure 1: see original paper], making vegetation extremely sensitive to natural and human (grazing) disturbances. Choir City has a temperate continental climate with average annual precipitation of 200–300 mm, average annual temperature of 1.8°C, maximum temperature of 22.9°C, and minimum temperature of -23.7°C. The windy period occurs from March to May, with average annual wind speed showing fluctuating changes [Figure 2: see original paper]. The average wind speed at 10 m height is 5.07 $\mathrm{m \cdot s^{-1}}$, with instantaneous wind speeds reaching 32.0 $\mathrm{mm \cdot s^{-1}}$. The area experiences frequent dust storms, with an average of 14.6 dust storm days per year. The average wind speed of sand-driving winds at 10 m height is 6.83 $\mathrm{m \cdot s^{-1}}$, greater than that in the northern Darhan region (6.46 $\mathrm{m \cdot s^{-1}}$) and the southern Zamyn Uud region (6.24 $\mathrm{m \cdot s^{-1}}$).

2.2 Data Sources

Wind dynamic data (May 2019 to July 2020) were obtained from a gradient meteorological observation station established by the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, in Choir City (108°21 E, 46°24 N). Observation heights at the meteorological station were 0.2 m, 2.0 m, 8.0 m, and 10.0 m. Instruments included: an automatic ultrasonic anemometer (model: WindSonic, manufactured by Vaisala, measurement range up to 60 $\mathrm{m \cdot s^{-1}}$), an integrated air temperature and humidity observation instrument (model: HMP155A-L, manufactured by Vaisala, measurement range -80–60°C), a soil temperature observation instrument, and a soil moisture content observation instrument (CS650, which can precisely measure soil moisture, temperature, and electrical conductivity). Data were recorded every 10 minutes. Sediment transport data (August 2019 to August 2020) were obtained from a self-made gradient large-capacity sand collector installed at the Choir City meteorological observation station [Figure 3: see original paper]. The sand particle collectors were installed at heights of 20 cm, 50 cm, 70 cm, and 120 cm above ground, with inlet openings of 16 cm × 16 cm square and collection boxes of 20 cm diameter cylinders. Other wind speed and dust storm data were obtained from the Choir City meteorological station.

2.3 Calculation Methods

2.3.1 Surface Roughness Surface roughness refers to the height at which near-surface wind speed decreases to zero in the atmospheric boundary layer, characterizing surface-atmosphere interactions and reflecting the impedance effect of surface features on atmospheric turbulence. It is an important concept in modern fluid mechanics and atmospheric science, and a crucial parameter in atmospheric boundary layer theory and wind-sand science with wide applications. There are many calculation methods for surface roughness. This study selected the wind speed ratio method using neutral stratification data at 0.8 m and 2.0 m heights:

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

where z_0 is surface roughness (m), z_1 and z_2 are observation heights (m), and u_1 and u_2 are wind speeds at corresponding heights ($\mathrm{m \cdot s^{-1}}$).

2.3.2 Friction Velocity In physics, friction velocity u_* reflects the magnitude of aerodynamic forces on particles. Existing wind erosion observations and experimental results indicate that when u_* exceeds a certain threshold (critical friction velocity), particles will detach from the surface and enter the air. Friction velocity is calculated using:

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

where u_* is friction velocity ($\mathrm{m \cdot s^{-1}}$), u_1 and u_2 are wind speeds at heights z_1 and z_2 ($\mathrm{m \cdot s^{-1}}$), and z_1 and z_2 are observation heights (m).

2.3.3 Critical Friction Velocity Critical friction velocity refers to the threshold value of friction velocity that can cause surface sand movement, calculated using:

$$u_{*t} = A\sqrt{\frac{\sigma - \rho}{\rho} gd}$$

where u_{*t} is critical friction velocity ($\mathrm{m \cdot s^{-1}}$), A is an empirical coefficient (0.1), σ is sand particle density (2650 $\mathrm{kg \cdot m^{-3}}$), ρ is air density (1.256 $\mathrm{kg \cdot m^{-3}}$), g is gravitational acceleration ($9.780327\ \mathrm{m \cdot s^{-2}}$), and d is local sand particle diameter (1.02 mm, as sand particles dominate locally) . The calculation results show that the critical friction velocity in Choir City is $0.5045\ \mathrm{m \cdot s^{-1}}$.

2.3.4 Critical Sand-Driving Wind Speed During atmospheric boundary layer airflow movement, surface sand materials are subjected to wind forces. When wind speed increases to a certain threshold, surface sand particles transition from a static state to motion. This threshold wind speed is defined as the critical sand-driving wind speed, an important indicator in wind-sand physics. Critical sand-driving wind speed is calculated using:

$$u_t = 5.75 u_{*t} \log_{10} \frac{z}{z_0}$$

where u_t is critical sand-driving wind speed ($\mathrm{m \cdot s^{-1}}$), u_{*t} is critical friction velocity ($\mathrm{m \cdot s^{-1}}$), z_0 is surface roughness (m), and z is calculation height (m).

2.3.5 Sand Drift Potential Sand drift potential (DP) represents the potential maximum sediment transport in a region over a certain period. The calculation formula is:

$$DP = \sum_{i=1}^{n} u_i^2 (u_i - u_t) t_i$$

where DP is sand drift potential (VU), u_i is wind speed at 10 m height greater than the critical sand-driving wind speed ($\mathrm{m \cdot s^{-1}}$), u_t is critical sand-driving wind speed ($\mathrm{m \cdot s^{-1}}$), and t_i is the duration of sand-driving wind (generally the percentage of observed sand-driving wind time to total observation time).

According to vector synthesis principles, combining DP from all directions yields the resultant drift potential (RDP) and resultant drift direction (RDD), representing a region' s net sediment transport capacity and overall sand transport direction, respectively. The ratio RDP/DP is called the wind direction variability index, reflecting wind direction combination characteristics. When $RDP/DP < 0.3$, it indicates high variability and complex wind conditions; when $0.3 \le RDP/DP \le 0.8$, it indicates moderate variability, generally corresponding to blunted or sharp double-peak wind conditions; when $RDP/DP > 0.8$, it indicates low variability and simple wind conditions.

3. Results

3.1 Sand-Driving Wind Characteristics

Based on wind speed data from the automatic meteorological observation station in Choir City, the average wind speed of sand-driving winds at 10 m height is $9.49\ \mathrm{m \cdot s^{-1}}$, with a maximum wind speed of $19.73\ \mathrm{m \cdot s^{-1}}$. Seasonal variation in sand-driving wind speed is significant, with the highest speeds in spring (10.47 $m \cdot s^{-1}$) and autumn (10.35 $m \cdot s^{-1}$), and lower speeds in summer (8.66 $m \cdot s^{-1}$) and winter (8.33 $m \cdot s^{-1}$), though the differences between seasons are not large. The frequency of sand-driving winds also varies by direction, with northerly winds (N, NNW, NW) occurring most frequently (31.53%) and easterly winds (E, ESE, SE) occurring least frequently (3.12%) [Figure 4: see original paper]. Overall, the region predominantly experiences northerly winds.

3.2 Sand Drift Potential and Transport Direction

Sand drift potential and transport direction can objectively reflect wind-sand activity intensity and overall sand material transport direction in a region. Areas with higher resultant drift potential typically have more uniform wind directions or stronger wind-sand activity, while areas with lower resultant drift potential have multiple wind directions or weaker wind-sand activity. Based on sand drift potential magnitude, previous scholars classified wind energy environments into three categories: low wind energy (<200 VU), moderate wind energy (200–400 VU), and high wind energy (>400 VU). The annual sand drift potential in Choir City is 735.96 VU, with an annual resultant drift potential of 428.76 VU and a resultant drift direction of SSW (195.06°). The wind direction variability index is 0.58, indicating a high wind energy environment with moderate variability and blunted double-peak wind conditions.

Sand drift potential varies significantly among wind directions. The WNW direction has the highest drift potential at 135.32 VU, accounting for 18.4% of total DP, while the ESE direction has the lowest at 3.12 VU, accounting for only 0.4% of total DP. Seasonal wind direction variability indices also differ, with spring and summer indices of 0.58 and 0.55 (moderate variability, double-peak wind conditions), and autumn and winter indices of 0.85 and 0.89 (low variability, indicating simple wind conditions). The annual sand drift potential rose diagram [Figure 5: see original paper] shows significant seasonal variations in DP, with resultant drift directions varying between 143.68° and 204.83°. Spring DP is the highest at 483.89 VU, accounting for 65.8% of annual DP with a resultant direction of 190.11°. Summer DP is 159.23 VU (21.6% of annual, direction 204.83°). Autumn DP is 19.84 VU (2.7% of annual, direction 143.68°). Winter DP is the lowest at 73.00 VU (9.9% of annual, direction 145.35°). Thus, the main sand transport energy concentrates in spring and summer, with some differences in transport direction among seasons, but all directions are southerly, indicating year-round influence of northerly airflow.

3.3 Aeolian Sand Flow Sediment Transport

Sediment transport is an important parameter for wind-sand engineering design. Previous observations have found that under certain wind conditions, saltating particles in aeolian sand flow interact with wind fields through a negative feedback mechanism that limits sediment transport to a certain value. Therefore, in areas with sufficient sand sources, wind transport capacity has certain limitations. Scholars have developed many sediment transport estimation models , but their calculation results vary greatly and are applicable to different regions, requiring accuracy verification before application. Research has shown that aeolian sand flow structure vertically generally follows an exponential function distribution. Based on observed data from Choir City, this study found that exponential functions fit the vertical distribution of aeolian sand flow well [Figure 6: see original paper]. Using integration methods, the total sediment transport over one annual cycle (August 2019 to August 2020) was calculated as $2.135\ \mathrm{t \cdot m^{-1}}$. Dividing this by sand-driving wind duration (2645 h) yielded an actual sediment transport rate of $2.24 \times 10^{-4}\ \mathrm{kg \cdot m^{-1} \cdot s^{-1}}$. Comparing actual transport with model calculations revealed that Bagnold, Kawamura, Sorensen, and Zingg models all overestimated sediment transport for Choir City, with the Zingg model showing smaller deviations and the Owen model being closest to actual values.

3.4 Critical Sand-Driving Wind Speed Variation and Influencing Factors

Critical sand-driving wind speed is a key parameter for wind erosion desertification, related to soil moisture, vegetation coverage, air density, soil particle size, soil texture, soil salinity, and gravitational acceleration. Based on 10 m height wind speed data, the region' s annual average critical sand-driving wind speed at 0.8 m height is $4.77\ \mathrm{m \cdot s^{-1}}$, with seasonal variation showing summer maximum ($6.77\ \mathrm{m \cdot s^{-1}}$), winter minimum ($3.63\ \mathrm{m \cdot s^{-1}}$), and spring and autumn in between ($6.64\ \mathrm{m \cdot s^{-1}}$ and $6.61\ \mathrm{m \cdot s^{-1}}$, respectively). Soil moisture and normalized difference vegetation index (NDVI) at 0.8 m height show synchronous variation with critical sand-driving wind speed, with excellent trend consistency [Figure 7: see original paper]. Critical sand-driving wind speed peaks in summer when soil moisture is lowest and vegetation coverage is highest, while winter shows the opposite pattern.

Soil moisture can reflect precipitation conditions to some extent. In spring 2020, Choir City experienced rising temperatures with decreasing soil moisture, leading to spring drought (high temperatures, low precipitation). Analysis of Choir City' s temperature and precipitation over recent years shows this phenomenon occurred in 7 out of 10 years, indicating that spring drought is not unusual but rather a frequent occurrence. Precipitation affects soil moisture, causing vegetation coverage changes that influence critical sand-driving wind speed. Both precipitation and NDVI are highest in summer, resulting in the highest critical sand-driving wind speed. [Figure 7: see original paper] shows reduced soil moisture in spring 2020, indicating decreased precipitation, combined with high wind speeds [Figure 4: see original paper] and low vegetation coverage, leading to severe spring drought and intense sand transport. Therefore, spring is the main period for wind erosion desertification occurrence in Choir City.

4. Discussion

Choir City in central Mongolia has extremely active wind erosion desertification processes and has become a northward expansion area for desertification in Mongolia. Urgent exploration of suitable wind-sand disaster prevention and ecological restoration technologies is needed. Comprehensive analysis of field observation and meteorological data yields the following conclusions: (1) The region has strong wind dynamics, with sand-driving wind average speed of 9.49 $m \cdot s^{-1}$ and maximum speed of 19.73 $m \cdot s^{-1}$. Northerly winds (N, NNW, NW) dominate, accounting for 31.53% of occurrences. The annual sand drift potential is 735.96 VU, resultant drift potential is 428.76 VU, and resultant drift direction is 195.06°, indicating a high wind energy environment. The wind direction variability index is 0.58, showing moderate variability and blunted double-peak wind conditions. (2) The underlying surface vegetation conditions are strongly influenced by natural precipitation and human grazing. Under strong wind forces, surface soil erosion is intense, with annual aeolian sand flow transport flux reaching 2.135 $t \cdot m^{-1}$. Located in the hinterland of the Mongolian Plateau, affected by Arctic and Pacific airflows, northerly and easterly winds prevail in spring and summer, while northwesterly winds dominate in autumn and winter.

Strong sediment transport in Choir City is related not only to powerful wind dynamics but also to local underlying surface conditions, which are mainly affected by vegetation types and livestock husbandry. The vegetation is mostly herbaceous with scattered low shrubs. Influenced by seasonal precipitation variations, spring vegetation conditions are extremely poor, providing little capacity to weaken strong winds or stabilize sand. Combined with the main windy season, strong wind forces, and low critical sand-driving wind speed, spring wind erosion desertification processes are particularly active. During grazing, livestock feeding and trampling cause varying degrees of damage to vegetation and soil, loosening surface soil structure and dramatically reducing wind erosion resistance, making it prone to wind erosion and aeolian sand flow formation. With rapid growth in herd numbers in recent years, severe overgrazing has exacerbated wind erosion problems, resulting in large surface aeolian sand flow transport flux.

5. Conclusions

Choir City in central Mongolia experiences extremely active wind erosion desertification processes and has become a northward expansion area for desertification in Mongolia, urgently requiring exploration of suitable wind-sand disaster prevention and ecological restoration solutions. Comprehensive analysis of field observations and meteorological data from August 2019 to August 2020 leads to the following conclusions:

(1) The region has strong wind dynamics for wind erosion desertification occurrence, with sand-driving wind average speed of 9.49 $m \cdot s^{-1}$ and maximum speed of 19.73 $m \cdot s^{-1}$. Sand-driving winds are predominantly northerly,

accounting for 31.53% of occurrences. The annual sand drift potential reaches 735.96 VU, with a resultant drift potential of 428.76 VU, classifying it as a high wind energy environment. This is substantially greater than the Taklimakan Desert (maximum annual DP of 285.67 VU), the Kumtag Desert (maximum annual DP of 733.40 VU), and the Tengger Desert (maximum annual DP of 733.40 VU), but similar to the Badain Jaran Desert' s maximum DP (733.40 VU). The wind direction variability index is 0.58, indicating moderate variability and blunted double-peak wind conditions, with a resultant drift direction of 195.06°.

(2) Annual wind dynamics fluctuate significantly, with spring being the windy season and drought period, representing the main time for wind erosion occurrence. The region' s location in a temperate continental climate zone with low precipitation (200–300 mm annually), frequent sunny days, dry climate, relatively flat terrain, and lack of tall mountain ranges allows airflows to travel long distances unimpeded, creating strong surface wind dynamics. Consequently, the annual sand drift potential (735.96 VU) is large, indicating a high wind energy environment.

(3) The underlying surface vegetation conditions are strongly affected by natural precipitation and human grazing. Under powerful wind forces, surface soil erosion is intense, with annual aeolian sand flow transport flux reaching 2.135 $t \cdot m^{-1}$. The region' s location in the Mongolian Plateau hinterland, influenced by Arctic and Pacific airflows, results in predominantly northerly and easterly winds in spring and summer, and northwesterly winds in autumn and winter.

(4) In addition to strong wind dynamics, intense sediment transport in Choir City is closely related to local underlying surface conditions, particularly vegetation types and livestock husbandry. The vegetation is mostly herbaceous with scattered low shrubs. Affected by seasonal precipitation variations, spring vegetation conditions are extremely poor, providing minimal capacity to weaken strong winds or stabilize sand. Combined with the main windy season, strong wind forces, and low critical sand-driving wind speed, spring wind erosion desertification processes are particularly active. During grazing, livestock feeding and trampling damage vegetation and soil, loosening surface soil structure and dramatically reducing wind erosion resistance, making it prone to wind erosion and aeolian sand flow formation. With rapid herd growth in recent years, severe overgrazing has exacerbated wind erosion problems, resulting in large surface aeolian sand flow transport flux.

(5) The number of annual dust storm days in Choir City from 1990 to 2018 showed a fluctuating increasing trend, positively correlated with recent wind speed changes, indicating gradually intensifying wind erosion desertification processes. With future construction of the China-Mongolia-Russia economic corridor, high-intensity economic development activities in Mongolia will increase rapidly. As a key node in this corridor with

convenient transportation and rich mineral resources, Choir City will become an important economic development zone, potentially exacerbating wind erosion desertification problems and threatening regional sustainable socio-economic development. Urgent in-depth research on wind erosion desertification processes and development of locally appropriate prevention measures are needed.

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