Analysis of Soil Wind Erosion Variation Characteristics and Key Influencing Factors in Mongolia over the Past Two Decades (Postprint)

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Abstract

Mongolia suffers from severe wind erosion desertification and has become one of the world' s major dust source regions. To gain an in-depth understanding of the spatiotemporal variation characteristics of wind erosion across Mongolia, this study utilized meteorological and remote sensing data including GLDAS, OLM, MOD13Q1, and NASA-SRTM within Mongolia, based on the GEE (Google Earth Engine) cloud computing platform, and employed the RWEQ model to calculate the soil wind erosion amount and spatiotemporal variation patterns, analyzing the main influencing factors and mechanisms of soil wind erosion. The results show that: (1) From 2001 to 2020, soil wind erosion in Mongolia exhibited a spatial distribution pattern of low in the north and high in the south; soil wind erosion occurred mainly in spring, with the erosion amount accounting for 45% of the annual total; over the past 20 years, the soil wind erosion amount showed a significant increasing trend overall, with the wind erosion modulus increasing at a rate of 0.06 t · hm-2 · a-1. (2) The changes in soil wind erosion in Mongolia are overall related to climate factors and the resulting changes in vegetation coverage, and are closely associated with the intensification of human activities such as grazing and cropland reclamation. The research results can provide important scientific reference for the prevention and control of wind erosion desertification in Mongolia.

Full Text

Preamble

Soil Wind Erosion Characteristics and Main Influencing Factors in Mongolia Over the Past 20 Years

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Abstract: Mongolia suffers from severe wind erosion and desertification, making it one of the world' s major dust sources. To comprehensively understand the spatiotemporal variation characteristics of wind erosion across Mongolia, this study utilized meteorological and remote sensing data from the Global Land Data Assimilation System (GLDAS) and MOD13Q1 platform on Google Earth Engine. Based on the Revised Wind Erosion Equation (RWEQ) model, we calculated soil wind erosion amounts and their spatiotemporal patterns in Mongolia, and analyzed the main influencing factors and their mechanisms.

Results show that: (1) Soil wind erosion in Mongolia exhibits pronounced seasonal variation within the year, with spring accounting for 45% of annual erosion, followed by autumn, while winter shows the weakest erosion. (2) From 2001 to 2020, soil wind erosion in Mongolia displayed significant interannual fluctuations and an overall increasing trend, with the wind erosion modulus growing at a rate of 0.06 $t \cdot hm^{-1} \cdot a^{-1}$. (3) Spatially, wind erosion shows clear heterogeneity, following a pattern of high values in the south and low values in the north, with severely eroded areas concentrated in the Gobi and desert regions bordering China in southern Mongolia. (4) Changes in soil wind erosion are primarily related to climate factors and resulting vegetation cover changes, and are also closely associated with intensified human activities such as overgrazing and cropland reclamation. These findings provide important scientific references for wind erosion and desertification control in Mongolia.

Keywords: RWEQ model; soil wind erosion; influencing factors; Mongolia

Introduction

Soil wind erosion represents one of the most significant causes of land degradation, affecting approximately one-third of the world' s land area, with severely wind-eroded land accounting for a substantial proportion. Wind erosion exerts numerous adverse effects on terrestrial ecosystems and human society, notably by substantially reducing soil fertility and plant productivity and degrading air quality. Furthermore, fine particles generated by surface wind erosion constitute a primary source of atmospheric aerosols, providing material sources for dust storms. Given the necessary conditions, large-scale sand and dust events can occur, as exemplified by the massive dust storm event in Mongolia in March 2021 that threatened vast areas of East Asia.

Quantitative assessment methods for soil wind erosion include direct field monitoring, wind tunnel simulation experiments, and isotope tracer-based erosion rate calculations. However, wind erosion monitoring equipment and wind tunnel experiments have certain limitations that make large-scale spatial assessment challenging. With the development of remote sensing technology, increasing numbers of scholars have utilized geographic information systems for wind erosion modeling, developing numerous models including SWEEP and RWEQ. The RWEQ model, in particular, has seen the widest application. Originally developed by the United States Department of Agriculture (USDA) as an empirical model for estimating soil loss in croplands, RWEQ has undergone several improvements and validations and has been widely applied globally. The model integrates natural processes with practical experience, combining field data with computer modeling to describe the physical processes of wind erosion. Previous studies have employed RWEQ to estimate potential wind erosion rates in China' s Hexi region, assess spatiotemporal patterns of soil wind erosion across China, and simulate the temporal dynamics of wind erosion in Central Asia during 2000–2015.

Mongolia experiences the highest frequency of dust storm events in East Asia and serves as the primary source region for dust storm disasters in the region. Previous studies have used expert-based methods to assess wind erosion rates and severity in Mongolia, indicating that approximately 70% of the country' s territory is affected by wind erosion, with the Gobi Desert considered the most severely affected area. Using meteorological observations and lidar, researchers found that wind erosion has generally increased across Mongolia. Other studies have employed GIS and remote sensing technology, using fuzzy mean clustering (FMC) methods to cluster four major environmental factors—vegetation coverage, terrain relief, soil dryness, and wind field intensity—and combined this with expert knowledge to produce wind erosion hazard maps for the Mongolian Plateau. However, these studies did not quantitatively assess long-term trends in wind erosion hazard. While some research has quantitatively analyzed wind erosion in Mongolia using the WEQ approach, such studies lacked analysis of long-term temporal trends. Currently, research on wind erosion in Mongolia remains limited, necessitating quantitative description and assessment of long-term wind erosion conditions. This study employs the RWEQ model to calculate wind erosion modulus across Mongolia, revealing spatiotemporal patterns and trends, and analyzing major influencing factors to deepen understanding of overall wind erosion characteristics and provide important references for sandstorm disaster prevention and desertification control in key areas.

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1. Study Area Overview

Mongolia is located in east-central Asia (87°44 -119°56 E, 41°32 -52°15 N) and is the world' s second-largest landlocked country, with an area of approximately 156.65×10^4 km^2. The country has an average elevation of 1580 m, with the lowest point (Khookh Nuur lake depression in the east) at 518 m and the highest point (Khuiten Peak in the west) at 4653 m. The capital, Ulaanbaatar, sits at 1310 m. Mongolia' s climate is distinctly continental, with four distinct seasons and large variations in annual and daily mean temperatures. Annual precipitation averages 120-250 mm, decreasing from north to south and from east to west, with precipitation concentrated in summer. According to data from Mongolia' s National Agency for Meteorology and Environmental Monitoring, southern Mongolia consists of desert and desert steppe regions, while the southeast comprises the Gobi Desert. Typical steppe vegetation extends east-west across central Mongolia, and forests are concentrated in the northern mountainous regions. Desert steppe, semi-desert, and desert areas account for approximately 41.3% of the country' s territory. These regions experience frequent strong winds, intense soil wind erosion, and fragile ecological environments, with average annual wind speeds of 4-6 $m \cdot s^{-1}$ and up to 30-120 dust storm days annually, posing threats to air quality in other East Asian countries.

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2. Materials and Methods

2.1.1 Wind Erosion Model

The RWEQ model comprehensively considers climatic conditions, soil properties, surface roughness, vegetation cover, and other environmental factors to estimate wind erosion amount, primarily based on Equation (1):

$$SWEQ = 150.71 \times (WF \times EF \times SCF \times K' \times COG)^{-0.3711}$$

where SWEQ represents the wind erosion modulus ($kg \cdot m^{-1}$), WF is the wind influence factor ($kg \cdot m^{-1}$), EF is the soil erodibility factor (dimensionless), SCF is the soil crust factor (dimensionless), K' is the surface roughness influence factor (dimensionless), and COG is the vegetation influence factor.

The specific calculation processes are as follows:

The wind influence factor (WF) is calculated as:

$$WF = W_f \times \rho \times \frac{g}{SW \times SD}$$

where Wf is the wind friction velocity ($kg \cdot m^{-1}$), is air density ($kg \cdot m^{-3}$), g is gravitational acceleration ($m \cdot s^{-2}$), SW is the soil moisture factor, and SD is the snow cover influence factor.

The soil erodibility factor (EF) is calculated as:

$$EF = \frac{(29.09 + 0.31Sa + 0.17Si + 0.33(Sa/Cl) - 0.95CaCO3 - 2.0OM)}{100}$$

where Sa is soil sand content (%), Si is soil silt content (%), Cl is soil clay content (%), OM is soil organic matter content (%), and $CaCO_3$ is calcium carbonate content (%).

The soil crust factor (SCF) is calculated as:

$$SCF = 1 + 0.0066(Cl)^2 + 0.021(OM)^2$$

The surface roughness influence factor (K') is calculated as:

$$K' = \cos(\alpha)$$

where α represents terrain slope, extractable from DEM data.

The vegetation influence factor (COG) represents the degree to which vegetation cover suppresses soil wind erosion under certain conditions. We used the maximum value composite method to obtain half-monthly data from MOD13Q1 and applied the pixel dichotomy model to calculate half-monthly vegetation coverage from 2001 to 2020:

$$FVC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}}$$

where FVC is fractional vegetation coverage, NDVI is the normalized difference vegetation index, NDVI is the NDVI value for bare soil pixels, and NDVI g is the NDVI value for fully vegetated pixels.

2.1.2 Trend Analysis Methods

We employed the Sen' s slope method and Mann-Kendall trend test to analyze trends in soil wind erosion and meteorological factors (wind speed, temperature, precipitation) in Mongolia from 2001 to 2020. These non-parametric tests require only sample independence and do not assume normal distribution. The slope is calculated as:

$$Slope = \text{Median}\left(\frac{x_j - x_i}{j - i}\right)$$

where x and x are the wind erosion modulus values or meteorological data for years i and j, and n is the total number of years in the study period. A positive slope indicates an increasing trend, while a negative slope indicates a decreasing trend.

2.2 Data Sources

Meteorological Data: Including wind speed, temperature, precipitation, snow depth, and soil moisture, all obtained from GLDAS2.1. GLDAS is an assimilation product jointly released by NASA' s Goddard Space Flight Center and NOAA' s National Centers for Environmental Prediction, based on satellite, land surface model, and ground observation data. GLDAS2.1 has a temporal resolution of 3 hours and spatial resolution of 0.25°, showing high consistency with ground meteorological observations.

Soil Data: Including soil organic matter content, clay content, silt content, sand content, and $CaCO_3$ content. Soil organic matter, clay, silt, and sand content data were obtained from the Harmonized World Soil Database, while $CaCO_3$ content came from the World Soil Information Database.

Vegetation Data: We selected NASA' s MOD13Q1 Level 3 standard product, with a temporal resolution of 16 days and spatial resolution of 250 m, suitable for calculating vegetation coverage.

Terrain Data: We used the Digital Elevation Model (DEM) jointly measured by NASA and the US Geological Survey, with a spatial resolution of 30 m. This is currently the highest-quality DEM dataset, with horizontal standard error of 6 m and vertical standard error of 10 m, used for calculating slope and surface roughness.

Other Data: Livestock data were obtained from Mongolia's National Statistics Office (www.1212.mn). Land use data were obtained from China's National Geomatics Center of China (GlobeLand30), which used over 10,000 Landsat images and Chinese environmental disaster reduction satellite multispectral imagery, offering high spatial resolution and data accuracy.

All raster data were resampled to a spatial resolution of 500 m and temporal resolution of one year, divided into four time periods for analysis. Annual wind erosion totals were obtained by summarizing the calculation results.

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3. Results

3.1 Spatial Variation Characteristics of Wind Erosion Modulus

The spatial distribution of soil wind erosion modulus in Mongolia shows considerable variation (Figure 2). The difference between maximum and minimum values ranges between 0-60 $t \cdot hm^{-1}$. Overall, soil wind erosion modulus follows a spatial pattern of low values in the north and high values in the south. Severe wind erosion occurs primarily in spring, accounting for approximately 45% of annual erosion, followed by autumn (September-November) at about 25%, summer (June-August) at about 20%, and winter (December-February) at only about 10% (Figure 3). The Mongolian Plateau experiences scarce precipitation and dry soils in spring, with vegetation not yet entering its rapid growth period and low vegetation coverage, resulting in very strong spring wind erosion. In winter, surface soil is frozen and often snow-covered, making erosion weakest. Both summer and autumn have good vegetation conditions, but summer precipitation is concentrated and soil moisture is significantly higher than in autumn, making summer erosion intensity lower than autumn. Meteorological observations indicate that dust events in Mongolia occur mainly in spring, consistent with our findings that wind erosion is strongest in spring.

From the perspective of interannual change rates (Figure 5), wind erosion change rates in the southern Gobi Desert region are approximately 0.5–1.0 $t \cdot hm^{-1} \cdot a^{-1}$, significantly higher than other regions. Northern Mongolia shows the lowest wind erosion and smallest changes. Southwestern Mongolia exhibits negative wind erosion change rates, indicating a declining trend in wind erosion, with average annual change rates of -0.01 to -0.6 $t \cdot hm^{-1} \cdot a^{-1}$. Overall, areas with high wind erosion modulus values experience rapid change rates, while low-value areas show slower change rates. Northern Mongolia is dominated by forest ecosystems with high vegetation coverage and stable forest ecosystems less affected by climate change and human activities, resulting in minimal wind erosion and small change rates. Southern Mongolia has fragile desert ecosystems with sparse vegetation, highly sensitive to climate change, thus showing large interannual variation rates. The declining wind erosion trend in southwestern Mongolia is primarily due to decreasing wind speeds in that region.

3.2 Temporal Variation Characteristics of Wind Erosion Modulus

From 2001 to 2020, soil wind erosion modulus in Mongolia showed a significant increasing trend ($R^2 = 0.2258$, $p < 0.05$), with the modulus increasing at a rate of 0.06 $t \cdot hm^{-1} \cdot a^{-1}$ (Figure 4). The wind erosion area in 2003 was significantly smaller than in other years, while the area expanded noticeably after 2010. Based on the temporal variation characteristics of wind erosion modulus, the 20-year period can be divided into two distinct phases: 2001–2010 was a period of decreasing wind erosion modulus ($R^2 = 0.3959$, $p < 0.05$), while 2011–2020 was a period of increasing wind erosion modulus ($R^2 = 0.427$, $p < 0.05$). The soil wind erosion modulus fluctuated in correspondence with wind speed variations, indicating that wind speed is the most important natural dynamic condition affecting soil wind erosion.

3.3 Analysis of Main Influencing Factors

3.3.1 Climate Factor Changes and Impacts The main climate factors affecting soil wind erosion are wind speed, temperature, and precipitation. Our analysis shows that annual maximum wind speed in Mongolia exhibited obvious fluctuations over the past 20 years, with a decreasing trend from 2001 to 2010 ($R^2 = 0.3959$, $p < 0.05$) and a significant increasing trend from 2011 to 2020 ($R^2 = 0.427$, $p < 0.05$). The spatial distribution of annual average wind speed change trends (Figure 8) shows significant increases in wind speed in the southern Gobi Desert region, corresponding to increased wind erosion, while central Mongolia experienced decreasing wind speed and reduced erosion. Correlation analysis between annual average wind speed and wind erosion modulus (Figure 9) reveals that only about 3.4% of Mongolia shows a negative correlation, while the vast majority (96.6%) shows positive correlation, particularly significant in southern and southwestern Gobi regions, confirming wind speed as the dominant natural factor.

Temperature and precipitation indirectly affect wind erosion by influencing soil moisture and plant growth. Over the past 20 years, most of Mongolia shows an increasing temperature trend, with the highest warming in the south at 0.06 °C · a^{-1} (Figure 10). Warming promotes surface water evaporation, leading to reduced soil moisture and increased erodibility, particularly in sparsely vegetated areas. Precipitation is closely related to surface soil water content, and reduced precipitation increases wind erosion risk. Overall, precipitation in Mongolia shows a significant increasing trend, but with large spatial variation—northern regions show clear precipitation increases, while central and southern regions, especially the Gobi area, show decreasing trends (Figure 11). The increased drought risk in southern regions, combined with wind action, leads to greater wind erosion.

3.3.2 Vegetation Coverage Changes and Impacts Vegetation cover increases surface roughness and reduces near-surface wind speed, thereby decreasing wind erosion risk. Analysis shows that vegetation coverage in most of Mongolia increased overall from 2001 to 2020, with rapid increases in some eastern areas reducing soil wind erosion (Figure 12). However, vegetation coverage decreased in some areas, particularly in southern and western desert steppe regions, increasing wind erosion risk.

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4. Discussion

4.1 Validation of Wind Erosion Modulus Results

To validate our RWEQ model results, we compared them with ^{137}Cs measurements from previous studies. The ^{137}Cs tracing technique is a common method for estimating soil erosion rates. Liu et al. used this method to calculate wind erosion modulus in the Mongolian Plateau, obtaining monitoring results of 2.736 $t \cdot hm^{-1} \cdot a^{-1}$ for Mongolia. Our RWEQ model yielded a 20-year average of 4.446 $t \cdot hm^{-1} \cdot a^{1}$, slightly higher but generally comparable. We conducted a correlation analysis between RWEQ-simulated wind erosion modulus and ^{137}Cs-measured values at the same geographic coordinates (Figure 13), showing significant correlation ($R = 0.91$, $p < 0.01$). The RWEQ model was initially developed by the USDA as an empirical model for cropland soil loss estimation and has been improved and validated for various applications, including assessments in Inner Mongolia and across China, as well as in Central Asia. However, results often require validation against other methods.

From the perspective of soil erodibility, Judger et al. evaluated the relative susceptibility of Mongolian soils to wind erosion, finding extensive high-erodibility areas from southern deserts and desert steppes to western sandy regions, broadly consistent with our severe wind erosion areas. Medium-erodibility areas cover western arid steppe and desert steppe regions, while low-erodibility areas extend from western to northern Mongolia. Mandakh et al. used the WEQ model to assess wind erosion in Mongolia, with spatial distribution patterns consistent with our conclusions.

4.2 Human Activity Changes and Impacts

Soil wind erosion is closely related to both climate conditions and underlying surface conditions, with human activities affecting erosion by altering the land surface. Overgrazing and coal mining have exacerbated land degradation in Mongolia. From 2001 to 2020, livestock numbers increased from 23.8 million to 67.1 million head, increasing at approximately 2.2 million head annually (Figure 14). Increased livestock pressure, combined with lenient grazing policies, has led to overgrazing across most pastures. Trampling and overgrazing damage surface soil structure, reduce vegetation cover in winter and spring, and increase wind erosion risk. Therefore, overgrazing may be a significant human factor contributing to increased soil wind erosion.

With rapid economic and social development, land use patterns have changed considerably. Land use conversion analysis (Figure 15) shows that 1733 km^2 of grassland was converted to cropland, with some unused land and forest also converted to cropland. Compared with traditional animal husbandry, crop cultivation causes more severe soil wind erosion. After conversion to cropland, human tillage dramatically alters soil structure, moisture, and nutrient conditions, intensifying wind erosion in local areas.

4.3 Spatial Heterogeneity of Coupled Influencing Factors

Temperature and precipitation indirectly affect wind erosion by influencing soil moisture and vegetation cover. From 2001 to 2020, both temperature and precipitation increased across Mongolia, and vegetation coverage also increased overall, which should theoretically suppress surface wind erosion. However, wind erosion still showed an overall increasing trend, seemingly contradictory. This discrepancy arises from significant spatiotemporal heterogeneity in the coupling of influencing factors. In severely wind-eroded areas, increased vegetation coverage has limited effect on reducing erosion because vegetation remains sparse and increases are not significant, while other factors like wind speed changes have more pronounced effects, particularly during the windy spring season. Research shows that different climate factors affect different regions, with drought having greater impacts on Gobi and desert areas. Therefore, at the national scale, wind speed is the dominant factor controlling soil wind erosion in Mongolia—the stronger the wind, the greater the erosion. Moreover, the extremely high proportion of arid desert land with strong wind erosion means that overall wind erosion in Mongolia continues to increase.

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5. Conclusions

This study analyzed the spatiotemporal dynamics of soil wind erosion and its main influencing factors in Mongolia from 2001 to 2020 using the RWEQ model. The main conclusions are:

1. Soil wind erosion in Mongolia shows clear seasonal variation, with 45% of annual erosion occurring in spring, followed by autumn, while winter shows the weakest erosion.
2. From 2001 to 2020, soil wind erosion in Mongolia exhibited significant interannual fluctuations and an overall increasing trend, with the wind erosion modulus increasing at a rate of 0.06 $t \cdot hm^{-1} \cdot a^{-1}$.
3. Wind erosion shows pronounced spatial heterogeneity, following a pattern of high values in the south and low values in the north. Severely eroded areas are located in the Gobi and desert regions in southern Mongolia bordering China. Spatial variation in wind erosion change rates is substantial, with high-value areas showing faster changes than low-value areas.
4. Changes in soil wind erosion are primarily related to climate factors and resulting vegetation cover changes, and are also closely associated with intensified human activities such as overgrazing and cropland reclamation. To effectively combat desertification hazards, Mongolia should strengthen scientific management of land resource development and utilization, and actively implement feasible control measures in severely desertified areas.

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