

Postprint: Valuation of Windbreak and Sand Fixation Services in the Shule River Basin Using the RWEQ Model

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Abstract

The Shule River Basin is situated in the inland northwestern region and serves as a critical node of the Belt and Road Initiative. In recent years, global change and increasing intensity of economic and social activities have led to problems such as rapid expansion of construction land and land desertification, affecting the sustainable development of regional ecology and socio-economy. Located in the center of the northern sand prevention belt, conducting an assessment of wind erosion prevention and sand fixation value in the Shule River Basin holds important ecological significance for constructing a regional ecological security pattern and ensuring sustainable basin development. Based on the Revised Wind Erosion Equation (RWEQ) model, the wind erosion prevention and sand fixation function and its value in the Shule River Basin from 2008—2018 were assessed. The results show: (1) The total wind erosion prevention and sand fixation amount in the Shule River Basin from 2008—2018 was 43.927×10^4 – 129.530×10^4 t · km², showing an upward trend. (2) The wind erosion prevention and sand fixation value in the Shule River Basin increased rapidly from 2008—2018, with the proportion of multi-year average value in descending order being: value of reducing land loss (99.46%), value of maintaining soil fertility (0.47%), value of maintaining soil organic matter (0.04%), and value of reducing economic losses in transportation (0.03%). (3) The basin's wind erosion prevention and sand fixation function is closely related to land use; areas with stronger capacity are mainly distributed in regions with higher vegetation coverage such as grassland and cultivated land; low-value areas are mainly distributed in regions where land use type is unused land. (4) Compared with social factors, natural indicator factors have a greater influence on the basin's wind erosion prevention and sand fixation function value. The research results can provide a basis for determining the subjects and objects of watershed ecological compensation and compensation standards.

Full Text

Abstract

The Shule River Basin, located in the northwest inland region of China, is a key node of the Belt and Road Initiative. In recent years, increasing global change and socioeconomic activities have led to rapid expansion of construction land and land desertification, affecting sustainable regional ecological and socioeconomic development. The Shule River Basin lies at the center of China's northern sand prevention belt, making evaluation of its wind prevention and sand fixation value ecologically significant for constructing regional ecological security patterns and ensuring basin sustainability. Based on the Revised Wind Erosion Equation (RWEQ) model, this study assessed the wind prevention and sand fixation value in the Shule River Basin from 2008 to 2018. Results show: (1) The total wind prevention and sand fixation quantity in the Shule River Basin from 2008 to 2018 ranged from 43.927×10^4 to 129.530×10^4 $t \cdot km^{-2}$, with an increasing trend in wind prevention and sand fixation capacity. (2) The value of wind prevention and sand fixation services increased rapidly from 2008 to 2018, with the multi-year average value composition (from highest to lowest) being: reduced land loss value (99.46%), maintained soil fertility value (0.47%), maintained soil organic matter value (0.04%), and reduced transportation economic loss value (0.03%). (3) Wind prevention and sand fixation function is closely related to land use; areas with stronger wind prevention and sand fixation capacity are mainly distributed in grasslands, croplands, and other regions with higher vegetation coverage, while low-value areas are mainly distributed in unused land. (4) Natural indicator factors have greater influence on wind prevention and sand fixation function value than socioeconomic factors. These findings can provide a basis for determining subjects, objects, and compensation standards for watershed ecological compensation.

Keywords: wind prevention and sand fixation services; Revised Wind Erosion Equation (RWEQ); value evaluation; Shule River Basin

Introduction

Wind prevention and sand fixation is a crucial ecological function in arid inland river basins, reflecting ecosystem stability in arid and semi-arid regions. Wind erosion refers to the process of surface material being eroded, abraded, and transported by wind, which can easily cause loss of soil nutrients and organic matter, leading to land desertification. By 2014, China's desertified land area reached approximately 2.61×10^6 km^2 , accounting for 27.2% of the country's territory, while sandy land area was about 1.73×10^6 km^2 , accounting for 18.0% of the territory. Desertification and the reduction of ecological service capacity seriously threaten human survival and development, attracting increasing scholarly attention. The Shule River Basin, located in northwest inland China, is the second largest river in the Hexi Corridor inland river system and a key node of the Belt and Road Initiative, representing a typically fragile ecosystem.

Influenced by global change, the Qilian Mountains provide abundant glacier meltwater, significantly increasing runoff in upstream mountainous areas and enabling rapid expansion of artificial oases. However, excessive expansion has caused river cutoff in middle and lower reaches, wetland shrinkage, vegetation degradation, land desertification, and salinization, making ecological problems increasingly prominent. Therefore, studying and evaluating wind prevention and sand fixation services in this basin is important for determining ecological compensation and strengthening environmental protection.

Wind prevention and sand fixation function refers to the ecosystem's ability to reduce wind-induced soil erosion through its structure and processes, thereby mitigating or avoiding harmful effects from dust storms. This soil-conserving, wind erosion-inhibiting function is an important protective measure providing services to wind erosion areas, significant for sand disaster control and ecological restoration in both affected and surrounding areas. Common models for this service include Bagnold's sediment transport model, the Wind Erosion Equation (WEQ), the Texas Erosion-Analysis Model (TEAM), Bocharov's descriptive model, the Wind Erosion Stochastic Simulator (WESS), the Wind Erosion Prediction System (WEPS), and the Revised Wind Erosion Equation (RWEQ). The RWEQ model is widely used in wind prevention and sand fixation research due to its simple operation, minimal data requirements, and comprehensive consideration of various factors affecting wind erosion.

This study uses the Shule River Basin as the research area, employing the RWEQ model to estimate wind prevention and sand fixation quantities from 2008 to 2018, and evaluates the function's value from four aspects: reduced land loss, maintained soil fertility, maintained soil organic matter, and reduced transportation economic losses. The results provide scientific basis for ecological environmental protection and future ecological compensation policy formulation in the basin.

1.1 Study Area Overview

The Shule River Basin is located in mid-latitude north temperate zone ($92^{\circ}11' \sim 98^{\circ}30' \text{ E}$, $38^{\circ}00' \sim 42^{\circ}48' \text{ N}$), one of the three major inland river basins in the Hexi Corridor and an important ecological barrier in northwest China. The basin covers a total area of $1.28 \times 10^5 \text{ km}^2$, with elevations ranging from 791 to 5569 m. The Shule River originates between the Tuole South Mountain and Shule South Mountain in the Qilian Mountains, flowing west through Subei Mongol Autonomous County, Yumen City, Guazhou County, and Dunhuang City. The region has a typical continental arid climate, with annual precipitation below 70 mm, strong evaporation, long sunshine hours (over 3000 mm evaporation), large temperature differences between cold winters and hot summers, and windy conditions with cool autumns and dry springs. The main soil types are marsh soil, meadow soil, and brown desert soil. Strong winds occur mainly from March to May, with maximum wind speed of $26 \text{ m} \cdot \text{s}^{-1}$ and dominant wind direction from the southwest.

1.2 Data Sources

Climate factor data were obtained from the China Meteorological Assimilation Driving Dataset (CMADS) for 2008–2018 from the National Tibetan Plateau Data Center. Snow cover factor data were derived from daily snow depth distribution data (spatial resolution 0.25°) from the Western China Environmental and Ecological Science Data Center. Soil data were obtained from the Western China Environmental and Ecological Science Data Center at 1:1,000,000 scale. DEM data were from the Geospatial Data Cloud. NDVI data were from NASA's USGS website. Land use data were from the GlobeLand30 global land cover dataset provided by the National Geographic Information Resources Directory Service System. All raster data were processed using WGS_1984_UTM_Zone_46N projection with 100 m spatial resolution.

1.3 Methods

1.3.1 Wind Prevention and Sand Fixation Quantity Estimation This study used the RWEQ model, which comprehensively considers climate, soil, vegetation, and terrain factors. The model calculates wind prevention and sand fixation quantity as the difference between potential wind erosion under bare soil conditions and actual wind erosion under vegetation cover:

$$G = SL_r - SL$$

where G is the annual wind prevention and sand fixation quantity per unit area ($t \cdot km^{-2}$), SL_r is the annual potential wind erosion per unit area ($t \cdot km^{-2}$), and SL is the annual actual wind erosion per unit area ($t \cdot km^{-2}$).

The potential wind erosion is calculated as:

$$SL_r = 2 \times Q_{rmax} \times e^{-(z/s)^2}$$

$$Q_{rmax} = 109.8 \times (WF \times EF \times SCF \times K')$$

The actual wind erosion is calculated as:

$$SL = 2 \times Q_{max} \times e^{-(z/s)^2}$$

$$Q_{max} = 150.71 \times (WF \times EF \times SCF \times K' \times C)$$

where z is the downwind distance (m), set to 150.71 m based on relevant research; s is the critical field length (m); Q_{rmax} is the maximum sediment transport capacity for potential wind erosion ($\text{kg} \cdot \text{m}^{-1}$); Q_{max} is the maximum sediment transport capacity for actual wind erosion ($\text{kg} \cdot \text{m}^{-1}$); WF is the climate factor; EF is the soil erodibility factor; SCF is the soil crust factor; K' is the soil roughness factor; and C is the vegetation factor.

The climate factor (WF) represents wind's ability to transport soil particles under conditions of rainfall, temperature, sunshine, and snow cover:

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

where wf is the wind force factor ($\text{m}^3 \cdot \text{s}^{-3}$), ρ is air density ($\text{kg} \cdot \text{m}^{-3}$), g is gravitational acceleration ($9.8 \text{ m} \cdot \text{s}^{-2}$), SW is the soil moisture factor, and SD is the snow cover factor (ratio of snow-free days to total study days).

The soil erodibility factor (EF) is calculated as:

$$EF = (29.09 + 0.31Sa + 0.17Si + 0.33Sa/Cl - 2.59OM - 0.95CaCO_3)/100$$

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

The soil crust factor (SCF) is:

$$SCF = 1/(1 + 0.0066Cl + 0.021OM)$$

The soil roughness factor (K') is:

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

where θ is the terrain slope calculated using ArcGIS 10.2 slope module.

The vegetation factor (C) is:

$$C = e^{-0.0438SC}$$

where SC is vegetation cover calculated from NDVI:

$$SC = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}$$

where $NDVI$, $NDVI_{max}$, and $NDVI_{min}$ are the actual, maximum, and minimum normalized difference vegetation index values.

1.3.2 Wind Prevention and Sand Fixation Value Calculation The total value (V , in yuan) was divided into four components: reduced land loss value (V_1), maintained soil fertility value (V_2), maintained soil organic matter value (V_3), and reduced transportation economic loss value (V_4).

1) **Reduced land loss value (V_1):**

$$V_1 = A \times h \times \rho_{soil} \times P_{land}$$

where A is the conserved topsoil area (hm^2), h is soil layer thickness (20 cm), ρ_{soil} is soil bulk density ($1.40 \text{ g} \cdot \text{cm}^{-3}$), and P_{land} is land opportunity cost ($47.75 \times 10^4 \text{ yuan} \cdot \text{hm}^{-2}$).

2) **Maintained soil fertility value (V_2):**

$$V_2 = G \times \sum_{i=1}^3 (N_i \times P_i / K_i)$$

where N_i is the content of element i (nitrogen, phosphorus, potassium) in soil (0.08%, 0.09%, 1.54%), P_i is fertilizer market price ($\text{yuan} \cdot \text{t}^{-1}$), and K_i is fertilizer element content (23.33% for urea, 52.41% for superphosphate, 24.6% for potassium chloride). National average retail prices were used: 2400, 800, and 2800 $\text{yuan} \cdot \text{t}^{-1}$ respectively.

3) **Maintained soil organic matter value (V_3):**

$$V_3 = G \times OM \times P_{OM}$$

where OM is soil organic matter content (1.23%) and P_{OM} is organic matter price (320 $\text{yuan} \cdot \text{t}^{-1}$).

4) **Reduced transportation economic loss value (V_4):**

$$V_4 = \frac{G}{\rho_{sand}} \times P_{clear}$$

where ρ_{sand} is sand bulk density ($1.35 \text{ g} \cdot \text{cm}^{-3}$) and P_{clear} is sand removal cost (15 $\text{yuan} \cdot \text{m}^{-3}$), based on inland engineering standards for dredging areas less than 5000 m^2 .

1.3.3 Analysis of Driving Factors Principal Component Analysis (PCA) reduces dimensionality to extract comprehensive indicators containing most information from multiple factors without redundancy. Based on the basin's natural and social environment, 11 indicators were selected (Table 1) to evaluate quantitative relationships with wind prevention and sand fixation services.

2 Results

2.1 Spatiotemporal Dynamics of Land Use in the Shule River Basin

Analysis of GlobeLand30 data shows that the main land use types are unused land and grassland, accounting for 85.6% and 11.5% of total area respectively. Cropland, forest, water, construction land, and wetland account for less than 3%. Unused land is distributed in northern and central areas, with some in the south. Grassland is mainly in southern Subei Mongol Autonomous County. Forest is in the southern mountainous area of Subei, relying on glacier and spring water. Water bodies are mainly in the central oasis area (Fig. 2).

From 2008 to 2018, land use changed significantly (Table 2). Grassland and cropland areas increased by 1488.49 km² (1.54%) and 150.50 km² (0.12%) respectively, showing fluctuating growth. Unused land and water areas decreased by 12.57×10^3 km² (1.21%) and 7.63 km² (0.02%) respectively. Forest and wetland increased slowly by 1.60 km² (0.05%) and 32.27 km² (0.12%). Construction land increased continuously from 9.23 km² to 13.83 km². These changes likely relate to ecological protection policies since the 13th Five-Year Plan, during which Jiuquan City completed afforestation of 12.57×10^3 km² and treated 32.27×10^3 km² of sandy land.

2.2 Wind Prevention and Sand Fixation Function

Based on multi-year average values per unit area under different surface covers (Table 3), the basin's unit area wind prevention and sand fixation quantity ranged from 129.00 to 371.35 t · km⁻², with total quantity of 43.93×10^4 t · km⁻² to 129.53×10^4 t · km⁻², showing an increasing trend consistent with previous research. Both potential and actual wind prevention and sand fixation quantities showed upward trends, possibly due to ecological protection policies.

Spatially, wind prevention and sand fixation capacity showed a pattern of higher values in southern grasslands, central croplands, and northwestern grasslands, with scattered high-value areas. From 2008 to 2018, Yumen City consistently had higher unit area values (>38 t · km⁻²), while Subei and Dunhuang had lower values (<20 t · km⁻²). Subei's southern area showed gradually increasing capacity, with 6.69 t · km⁻² growth from 2008 to 2018 (11.70% increase). Guazhou and Dunhuang also showed increases of 13.01% and 12.98% respectively.

2.3 Retention Rate of Wind Prevention and Sand Fixation

The retention rate showed overall growth from 2008 to 2018 (Fig. 4), with significant increases in southern Subei County, Yumen City, and Guazhou County. Using 2013 as a node, different periods showed varying retention rates. The retention rate is closely related to surface cover, with forest having the strongest capacity but only accounting for 0.02% of the basin area. Grassland contributed most to basin-wide wind prevention and sand fixation, with annual average quantity of 68.22×10^4 t · km⁻², followed by cropland (23.03×10^4 t ·

km^{-2}), water bodies ($1.14 \times 10^4 \text{ t} \cdot \text{km}^{-2}$), and forest ($0.02 \times 10^4 \text{ t} \cdot \text{km}^{-2}$).

2.4 Value of Wind Prevention and Sand Fixation Function

The total value of vegetation's wind prevention and sand fixation function increased from 741.559×10^4 yuan in 2008 to 2196.925×10^4 yuan in 2018 (Table 4). The value composition was dominated by reduced land loss value (99.46%), followed by maintained soil fertility value (0.47%), maintained soil organic matter value (0.04%), and reduced transportation economic loss value (0.03%). The vegetation ecosystem plays a crucial role in maintaining soil fertility and reducing land loss.

2.5 Influencing Factors of Wind Prevention and Sand Fixation Services

PCA analysis using SPSS 25.0 extracted two main components (Table 5). The first component had an eigenvalue of 8.358, explaining 75.977% of variance. The second component had an eigenvalue of 1.372, explaining 12.471% of variance. Together they explained 88.448% of total variance, meeting analysis requirements.

The component loading matrix (Table 6) shows vegetation index, population density, and soil moisture had strong effects in PC1, indicating that increasing vegetation coverage enhances soil water retention and reduces wind erosion. In PC2, annual average temperature had the largest loading, while GDP per capita and population density were weaker, suggesting natural factors dominate wind prevention and sand fixation function.

Comprehensive scores (Table 7) were calculated from component contributions. Positive scores indicate enhanced wind prevention and sand fixation capacity and improved ecological environment, while negative scores indicate poor capacity and prominent ecological problems requiring attention.

3 Discussion

The increasing trend in unit area wind prevention and sand fixation quantity mainly relates to land use changes. Since the 13th Five-Year Plan, Jiuquan City has focused on green development, completing $12.57 \times 10^3 \text{ km}^2$ of afforestation and treating $32.27 \times 10^3 \text{ km}^2$ of sandy land. Increased vegetation coverage enhances soil water retention, reduces wind erosion, and improves basin-wide wind prevention and sand fixation capacity. The contribution of land cover changes to sand fixation shows an overall upward trend, consistent with previous research.

PCA results show climate factors like temperature and precipitation strongly influence wind prevention and sand fixation services, representing dominant factors affecting soil wind erosion. Increased rainfall enhances soil cohesion through

capillary forces and promotes vegetation growth, strengthening resistance to wind erosion. However, rising temperatures increase evapotranspiration, reducing soil moisture and making surfaces more susceptible to wind erosion. Beyond climate factors, vegetation index significantly affects wind prevention and sand fixation function by enhancing soil anti-erodibility and influencing regional environmental conditions like temperature, soil moisture, and evapotranspiration. Southern Subei Mongol Autonomous County has large grassland areas that provide wind prevention and sand fixation, water conservation, and soil organic matter enhancement, likely causing spatial differences in basin-wide function.

This study provides beneficial exploration of wind prevention and sand fixation services and value evaluation. Model parameters were processed based on existing research, such as using 150.71 m for downwind distance in small watershed studies, though this value's appropriateness requires further investigation. The integrated vegetation factor is typically the product of flat residue, standing residue, and crop coverage, but due to local practices of processing crop residues into livestock feed, NDVI data were used as a substitute, potentially affecting results. Meteorological data were daily averages, making it difficult to accurately monitor instantaneous rainfall and wind speeds. Future research should integrate multi-source data to obtain higher-resolution meteorological data, avoiding rough assessments of soil wind erosion rates and providing basis for determining ecological compensation subjects, objects, and standards.

4 Conclusions

- 1) From 2008 to 2018, wind prevention and sand fixation function in the Shule River Basin showed an overall increasing trend. Both potential and actual wind prevention and sand fixation quantities increased at similar rates, while total wind prevention and sand fixation quantity increased substantially from 43.927×10^4 to 129.530×10^4 $t \cdot km^{-2}$, mainly due to land use changes. During this period, cropland and grassland areas increased, while unused land and water areas decreased.
- 2) The wind prevention and sand fixation value increased from 741.559×10^4 yuan in 2008 to 2196.925×10^4 yuan in 2018, dominated by reduced land loss value (99.46%), followed by maintained soil fertility value, maintained soil organic matter value, and reduced transportation economic loss value.
- 3) Spatial distribution of wind prevention and sand fixation function showed significant differences. High-capacity areas were mainly distributed in southeastern Subei Mongol Autonomous County, central Guazhou and Yumen, northwestern Dunhuang, and northern Subei Autonomous County. Low-capacity areas were mainly in northern and southern Subei, northern and southern Guazhou, most of Yumen and Dunhuang.
- 4) Among natural factors, vegetation index had the greatest effect on wind prevention and sand fixation function, indicating vegetation's important

role in reducing wind speed and stabilizing sand flow.

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Evaluation of wind prevention and sand fixation function in Shule River Basin based on RWEQ model

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