Postprint of Evaluation of Windbreak and Sand Fixation Effectiveness of Different Sand Barrier Combination Measures for Mobile Dunes in the Mu Us Sandy Land

Authors: Shi Lin, Li Hongyue, Zhao Yuxing, REN Yuyan, He Jinjun, Yu Fengqiang, Has-Erdene, Hasi Erdun

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Abstract

To understand the windbreak and sand fixation benefits of combined measures configuring sand-fixing plant species with Salix psammophila regenerated sand barriers, polylactic acid (PLA) sandbag barriers, and straw rope sand barriers in the Mu Us Sandy Land, measurements of wind speed at different heights, near-surface sediment transport, and erosion-deposition patterns within barriers under various combined measures were conducted to comparatively analyze the windbreak and sand fixation benefits of several sand barrier combined measures under different materials, slope positions, and specifications. The results showed that: (1) Under the 1 m$×1*mspecification,thecombinedmeasuresofSalixpsammophilaregeneratedsandbarriersandstrawropesar*
*surfacewindspeed,reaching*80.29×$3 m specification of straw rope and PLA sand barrier combined measures was only 58.14% and 57.88%, respectively; (2) The reduction rate of sediment transport exhibited the following pattern: Salix psammophila > straw rope > PLA, and showed a decreasing trend with increasing specification size, among which the sand-blocking effect of the Salix psammophila regenerated sand barrier combined measure was relatively stable, while the other two were less stable; (3) The microtopography within barriers under various measures was primarily controlled by NW~NNW wind directions, with different sand barrier materials exhibiting distinct morphological characteristics within barriers and overall erosion being dominant. The straw rope sand barrier combined measure showed the maximum relative erosion depth within barriers, followed by the PLA sand barrier measure, while the Salix psammophila sand barrier measure exhibited a weak erosion-deposition state primarily within the erosion depth range of -10~5 cm; however, the relative erosion depth range showed a decreasing trend with increasing specification

size and slope position. Comprehensive analysis suggests that the artificial sand-fixing vegetation system combining Salix psammophila regenerated sand barriers with broadcast-seeded sand-fixing plant species is the most stable and provides optimal windbreak and sand fixation benefits, representing a relatively suitable technical measure for promoting vegetation restoration through sand barriers on mobile dunes in the Mu Us Sandy Land, while other combined measures may be appropriately adopted depending on the availability of sand barrier materials, transportation conditions, as well as the aeolian sand environment and restoration objectives.

Full Text

Benefit Evaluation of Wind Prevention and Sand Fixation Under Combined Sand Barrier Measures in Mobile Dunes of the Mu Us Sandy Land

SHI Lin[1], LI Hongyue[2], ZHAO Yuxing[1], REN Yuyan[1], HE Jinjun[1], YU Fengqiang[3], Hasi Eerdun[4]

[1]Ordos Research Institute of Forestry and Grassland Science, Ordos, Inner Mongolia 017010, China
[2]Beijing Guangqumen Middle School, Beijing 100001, China
[3]Ordos Forestry and Grassland Development Center, Ordos, Inner Mongolia 017010, China
[4]School of Natural Resources, Faculty of Geographic Sciences, Beijing Normal University, Beijing 100875, China

Abstract

To understand the wind prevention and sand fixation benefits of combined measures using sand-fixing plant species with regenerative *Salix psammophila* sand barriers, polylactic acid (PLA) sandbag barriers, and straw rope sand barriers in the Mu Us sandy land, we conducted comparative analyses of these barrier combinations under different materials, slope positions, and specifications. Measurements included wind speed at various heights, near-surface sediment transport, and erosion-accumulation patterns within barriers. The results demonstrated that wind speed reduction was most effective for the 1 m × 1 m *S. psammophila* regenerative barrier and straw rope barrier, reaching up to 80.29% and 78.49%, respectively. The 3 m × 3 m straw rope and PLA barrier combinations showed wind prevention effectiveness of 58.14% and 57.88%, respectively. The sand transport reduction rate followed the pattern: *S. psammophila* > straw rope > PLA, with values increasing as barrier specifications decreased. The *S. psammophila* regenerative barrier combination exhibited stable sand-blocking effects, while the other two measures showed relatively poor stability. Under all treatments, microtopography within barriers was primarily controlled by wind direction (NW to NNW), with morphological characteristics varying by barrier material. Overall erosion dominated, with straw rope barrier combinations showing the greatest relative erosion depth, followed by PLA barriers, while *S. psammophila* barriers demonstrated weak erosion-accumulation within the -10 to 5 cm range. Relative erosion depth decreased with increasing barrier specification and slope position. Comprehensive analysis indicates that the artificial sand-fixation vegetation system combining *S. psammophila* checkerboard barriers with broadcast seeding of sand-fixing species is the most stable and optimal for wind prevention and sand fixation in mobile dunes of the Mu Us sandy land. Other combinations may be appropriately adopted based on material availability, transportation conditions, aeolian environment, and management objectives.

Keywords: mobile dune; sand barrier; combined measures; windbreak and sand fixation; Mu Us sandy land

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1. Study Area Overview

The study area is located in the Tuke Town sandy region of Uxin Banner, Inner Mongolia, situated in the hinterland of the Mu Us sandy land (38°53 26 -38°53 47 N, 109°13 47 -109°14 23 E). The surface landscape is dominated by barchan dunes and barchan dune chains oriented at 25°-35°, with heights generally ranging from several meters to over ten meters. The windward slopes are gentle (approximately 10°-20°), while the leeward slopes are steep (approximately 28°-33°). The region experiences a semi-arid monsoon climate with dry, cold, windy winters and hot, rainless summers. The annual average temperature is 7.2°C, with annual precipitation of 211-379 mm and average wind speed of 3 $m \cdot s^{-1}$. Wind-sand activities are frequent from March to May. The vegetation consists mainly of psammophytes, including *Artemisia ordosica*, *Agriophyllum pungens*, *Corispermum mongolicum*, *Psammochloa villosa*, *Salix psammophila*, and *Hedysarum laeve*.

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2. Materials and Methods

2.1 Experimental Materials

The experiment utilized three sand barrier materials: *Salix psammophila*, straw rope, and polylactic acid (PLA) fiber, combined with locally adapted pioneer sand-fixing plant species. *S. psammophila* barriers employed living one- to two-year-old branches with regenerative capacity. PLA barriers are novel bio-based degradable fiber tube barriers, manufactured as polymer cylindrical fabrics from cassava and starch raw materials with diameters of 8-10 cm. Straw rope barriers were made from wheat straw using a twist weaving method, with two ropes twisted together for use. Following barrier establishment, sand-fixing plant species (*Hedysarum laeve* and *Artemisia sieversiana*) were broadcast-sown during the rainy season to promote rapid vegetation recovery, after which vegetation was allowed to regenerate naturally.

2.2 Experimental Design and Measurements

2.2.1 Experimental Layout In late May, during the vegetation dormancy period, we selected independent, gentle barchan mobile dunes (vegetation coverage < 0.1) with similar size, orientation, and slope, free from surrounding obstacles. Three types of checkerboard sand barrier combinations were established on separate dunes at 1 m × 1 m and 3 m × 3 m specifications. Based on barchan dune characteristics, barriers were primarily installed from the dune toe to the crest on windward slopes, leaving the dune top unbarriered to utilize wind erosion to flatten the crest and restore natural vegetation, thereby achieving both wind prevention and material cost savings. Adjacent barrier plots were spaced 15-20 m apart to minimize interference.

2.2.2 Wind Prevention Effectiveness Measurement Wind speed measurements were conducted synchronously at the center of barrier grids on the middle windward slope, with simultaneous observations at corresponding heights on adjacent bare dunes (control). Cup anemometers were installed at four heights (0.1 m, 0.3 m, 0.5 m, and 2.0 m), with data collection intervals of 10 minutes. Each measurement lasted 20-30 minutes, adjusted according to wind force and stability. During the observation period, wind direction ranged from NW to NNW (43.75% frequency) and NW to NNE (39.20%), with wind speeds of 4-14 $\mathrm{m \cdot s^{-1}}$ and average speeds of 8.94 $\mathrm{m \cdot s^{-1}}$ and 9.17 $\mathrm{m \cdot s^{-1}}$, respectively. Wind prevention effectiveness at height h was calculated as:

$$E_h = \frac{V_{h0} - V_h}{V_{h0}} \times 100\%$$

where E_h is wind prevention effectiveness at height h (%), V_{h0} is average wind speed at height h on control dunes ($\mathrm{m \cdot s^{-1}}$), and V_h is average wind speed at height h within barriers ($\mathrm{m \cdot s^{-1}}$). The 2.0 m height wind speed served as the reference benchmark.

2.2.3 Sediment Transport Measurement Synchronous sediment transport measurements were conducted using stepwise sand collectors (30 cm height, 20 collection boxes, 2 cm × 2 cm inlet area) installed at the center of different barrier specifications on upper-middle and lower slopes. Observations began when threshold wind speeds were reached, with each session lasting 20-30 minutes and including three parallel experiments. Collected sand samples were weighed to 0.001 g precision to obtain sediment transport rates. The reduction rate was calculated as:

$$Q = \frac{Q_0 - Q_t}{Q_0} \times 100\%$$

where Q is the sediment transport reduction rate (%), Q_0 is the sediment transport rate on control bare dunes ($g \cdot min^{-1}$), and Q_t is the sediment transport rate at measurement points ($g \cdot min^{-1}$).

2.2.4 Microtopography Measurement Following the spring wind season, microtopography within barriers was measured using the pin-insertion method. Three checkerboard grids of each specification were selected on lower and upper-middle slope positions. A horizontal reference plane was established at the original barrier height, supported by rigid iron mesh fixed with wooden stakes. Pins were inserted at 0.5 m intervals along grid intersections, and vertical distances (D) from the reference plane were measured to obtain relative erosion-accumulation depths ($H = D$ - barrier height). Surface morphology was modeled using Surfer 15.3 software with Kriging interpolation to create 3D surfaces and calculate area percentages of different relative erosion depth ranges.

3. Results

3.1 Wind Prevention Effectiveness Under Different Barrier Combinations

Wind prevention effectiveness reflects the capacity of surface obstacles to reduce wind speed. All barrier treatments effectively reduced near-surface wind velocity, with material type, barrier height, and porosity being primary influencing factors. Using simultaneous control dune measurements as a baseline, effectiveness was compared across four heights.

Maximum wind prevention effectiveness occurred at 0.1 m height for all three barrier materials, reaching 80.29% for *S. psammophila*, 78.49% for straw rope, and 70.85% for PLA at 1 m × 1 m specification. Effectiveness decreased with increasing height and barrier specification, consistent with previous research. At 0.1 m height, *S. psammophila* and straw rope barriers showed significantly higher effectiveness than PLA ($P < 0.05$), while differences between *S. psammophila* and straw rope were not significant. At 0.3 m height, the 1 m × 1 m *S. psammophila* barrier maintained superior effectiveness (69.79%), significantly higher than PLA (61.67%) but similar to straw rope (65.40%). At 0.5 m and 2.0 m heights, differences among materials became insignificant across all specifications.

3.2 Sediment Transport Reduction Under Different Barrier Combinations

All barrier combinations reduced near-surface sediment transport rates, with reduction magnitude varying by material, specification, and slope position. The reduction rate pattern was: *S. psammophila* > straw rope > PLA, with values ranging from 46%-99%, 12%-51%, and 10%-71%, respectively. The 1 m

× 1 m *S. psammophila* barrier achieved the highest reduction rate (96.88% on upper-middle slope, 97.22% on lower slope), significantly outperforming other treatments. Reduction rates decreased with increasing barrier specification for all materials. Spatially, upper-middle slopes consistently showed higher reduction rates than lower slopes. The straw rope barrier outperformed PLA at 1 m × 1 m specification, but this advantage diminished at 3 m × 3 m. The *S. psammophila* regenerative barrier demonstrated the most stable sand-blocking effect, while straw rope and PLA barriers showed less stable performance, particularly at larger specifications and higher slope positions.

3.3 Concave Surface Characteristics Within Barriers

Sediment transport changes reflect surface erosion-accumulation processes. Checkerboard barriers not only block incoming sand flux but also stabilize original sand surfaces. Under long-term vortex action, stable concave surfaces form within grids, representing the most direct manifestation of barrier effectiveness. Following vegetation regeneration, distinct topographic variations emerged among treatments.

The *S. psammophila* barrier exhibited a "dustpan-shaped" concave surface with the lowest erosion point at the upwind center and deposition zones along surrounding barriers. PLA and straw rope barriers showed "funnel-shaped" surfaces with central erosion points, more pronounced in straw rope treatments. Erosion dominated across all measures, with lower slopes showing greater erosion depth and area than upper-middle slopes. For straw rope barriers, relative erosion area reached 96.88% (upper-middle) and 97.22% (lower) at 3 m × 3 m specification—the highest among all treatments. The *S. psammophila* barrier showed the smallest erosion area, with depth ranges of -10 to 5 cm dominating, indicating weak erosion-accumulation status. Both erosion depth range and relative depth increased with barrier specification, with larger grids showing more irregular surfaces and greater depth differentials between center and periphery.

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4. Discussion

The combined measures of sand barriers with sand-fixing plants altered the physical structure of mobile dune surfaces. All three barrier types effectively reduced wind speed and blocked sand transport, with average wind velocity and sediment flux lower than the mobile dune control.

The porous, upright *S. psammophila* regenerative barrier produced strong cumulative wind reduction effects, while the low, smooth, dense straw rope and PLA barriers allowed airflow to accelerate after passing over obstacles. This aligns with previous findings that barrier effectiveness depends primarily on structural differences. Small-scale vortices formed within dense barriers, creating unstable wind fields that diminished with increasing barrier size and measurement height. Liu (2012) similarly reported that larger barrier specifications reduce near-surface wind control capacity, enhancing erosion.

Effectiveness varied spatially across dune positions. The regenerative *S. psammophila* barrier, with its sprouting capacity, consistently reduced sediment transport, with sand accumulation extending farther as slope position and wind speed increased. In contrast, straw rope and PLA barriers, being shorter and denser, forced sand-laden airflow to rise, reducing flow beneath barrier height and rapidly decreasing wind speed. However, this caused sediment transport to elevate to new heights, increasing surface flux and creating unstable sand-blocking effects, particularly at higher slope positions. Straw rope barriers outperformed PLA at 1 m × 1 m specification due to surface roughness, but this advantage decreased at 3 m × 3 m.

Microtopographic analysis revealed that erosion dominated across treatments, with lower slopes showing greater erosion depth than upper-middle slopes. This may reflect the transition to interdune lowlands with sparse vegetation, where the combined barrier-plant measures accelerated vegetation recovery, limiting sand supply for replenishment after erosion. This non-correlative relationship between slope position and erosion depth warrants consideration in future applications.

While previous studies have evaluated barrier performance based on wind and sand control metrics, we argue that post-establishment erosion-accumulation characteristics within barriers provide the most direct assessment of engineering effectiveness. Objective evaluation requires independent analysis of each indicator followed by correlation analysis. This study' s barrier installation methods and plant species selection were based on regional forestry engineering practices, which may limit broader applicability. Further research should examine long-term soil impacts, optimized plant species selection, and ecological benefits after stabilization.

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5. Conclusions

Wind prevention and sand fixation benefits under combined barrier-plant measures varied significantly by barrier material, specification, and installation position. Key findings include:

1. **Wind prevention effectiveness** was highest for the 1 m × 1 m *S. psammophila* regenerative barrier (80.29% at 0.1 m height), followed by straw rope (78.49%) and PLA (70.85%). Effectiveness decreased with increasing height and barrier specification. At 3 m × 3 m, straw rope and PLA barriers showed similar effectiveness (58.14% and 57.88%, respectively).
2. **Sand-blocking effects** were strongest and most stable for *S. psammophila* barrier combinations. At 1 m × 1 m, straw rope barriers out-

performed PLA, but performance became unstable at larger specifications and higher slope positions.

3. **Microtopography** was primarily controlled by NW-NNW wind direction. All barrier types showed similar morphological patterns transitioning from weak erosion zones to strong central erosion areas, with minimal variation between slope positions for the same material.
4. **Erosion depth** was greater on lower slopes, particularly evident for larger specifications. Straw rope barriers exhibited the largest relative erosion area (96.88% upper-middle, 97.22% lower at 3 m × 3 m).
5. The *S. psammophila* checkerboard barrier combined with local sand-fixing plants formed the most stable system with long protection duration, enabling rapid initial stabilization and sustained sand fixation. Post-establishment pruning can provide fodder, enhancing comprehensive management benefits beyond mechanical barriers alone.

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