Postprint: Inhibitory Effects of Three Typical Herbaceous Plant Architectures on Sand Surface Wind Erosion

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Abstract

Plants inherently possess unique functions to maintain habitat stability, with plant morphology being one of the key functional elements. Investigating the surface wind erosion resistance of different morphological types of herbaceous plants in sandy desert areas can provide important scientific references for formulating ecological restoration measures. Through wind tunnel experiments, the sand surface wind erosion rates of herbaceous plants with three morphologies (prostrate, spherical, and clump) were measured under five coverage conditions (25%, 30%, 35%, 40%, and 45%), and the wind erosion inhibition rates of each morphology were analyzed. The results showed: (1) As coverage increased for the three morphological types, both aerodynamic roughness and wind speed reduction increased gradually. At lower coverage, the differences in wind erosion inhibition rates among different plant morphologies were substantial, with spherical and prostrate morphologies exhibiting relatively higher sand fixation capacity, while clump morphology showed relatively lower sand fixation capacity; plant morphologies with higher wind erosion inhibition efficiency could achieve sand fixation effects comparable to those of morphologies with lower efficiency under higher coverage conditions. (2) At 30% coverage, the wind erosion inhibition efficiencies of prostrate and spherical plants were 47.55% and 55.70%, respectively, which approached the wind erosion inhibition efficiencies of clump plants at 40% coverage (48.46%) and 45% coverage (56.94%). (3) The wind erosion inhibition efficiencies of all three morphological types increased with increasing coverage; the lower the coverage, the greater the differences among the three types, and conversely, the higher the coverage, the smaller the differences; among the three plant morphologies, the wind erosion rate was lowest for prostrate, intermediate for spherical, and highest for clump; the wind erosion inhibition efficiency was highest for prostrate, intermediate for spherical, and lowest for clump.

Full Text

Study on Wind Erosion Inhibition by Three Typical Herbaceous Plant Forms on Sand Surface

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Abstract

Plants possess unique functions to maintain habitat stability, with plant form being one of the main factors. Studying the wind erosion resistance of different herbaceous plant forms in sandy desert areas can provide important scientific references for ecological restoration measures. Through wind tunnel experiments, the sand surface wind erosion rate was measured for three plant forms (creeping, globular, and plexiform) under five coverage conditions (25%, 30%, 35%, 40%, and 45%), and the wind erosion inhibition rate of each form was analyzed. The results showed that: (1) For all three plant forms, aerodynamic roughness and wind speed reduction gradually increased with increasing coverage. At low coverage, the wind erosion inhibition rate differed significantly among different plant forms; globular and creeping plant forms had relatively higher sand fixation capacity, while plexiform plant forms had relatively lower capacity. Plant forms with higher wind erosion inhibition efficiency could achieve sand fixation effects equivalent to those with lower efficiency at higher coverage conditions. (2) At 30% coverage, the wind erosion inhibition efficiency of creeping and globular plants was 47.55% and 55.70%, respectively, which was close to the inhibition efficiency of plexiform plants at 40% (48.46%) and 45% (56.94%) coverage. (3) The wind erosion inhibition efficiency of all three herbaceous plant forms increased with coverage; the smaller the coverage, the greater the difference among the three forms, and vice versa. The wind erosion rate was lowest for creeping, followed by globular, and highest for plexiform; conversely, wind erosion inhibition efficiency was highest for creeping, followed by globular, and lowest for plexiform.

Keywords: herbaceous plants; plant form; wind tunnel experiment; wind erosion rate; wind erosion inhibition efficiency

Introduction

Plants can effectively inhibit surface wind erosion and serve as a primary measure for controlling sandy desertification [1,2]. The above-ground portions of plants protect the surface through multiple mechanisms, including covering portions of the surface, dissipating wind momentum, and trapping eroded material to promote deposition [3]. The effectiveness of wind erosion control depends on various plant characteristics, such as height, width, form, porosity, branch elasticity [4], root characteristics [5], and distribution patterns including coverage and arrangement [6,7]. Numerous studies have investigated the relationships between wind erosion and trees/shrubs [8], crop residues [9], and tillage practices [10], as well as the effects of plant arrangement [11]. However, research on herbaceous plants and the relationship between different plant forms and wind erosion remains relatively limited, focusing primarily on single plants' effects on wind speed. Zhang et al. [12] studied different forms and cylindrical models, finding that flexible plants with larger upper portions and smaller lower portions had better sand-blocking effects. Wang Chenglong [13] investigated the effects of four plant species on wind speed, finding significant differences in the most influential heights. Gillies et al. [14] studied different forms and found significant differences in drag coefficients. While these studies enhanced understanding of single-plant wind protection, research on the protective effects of different plant populations and the effectiveness of herbaceous plants in controlling wind erosion needs strengthening.

Although herbaceous plants account for a small proportion of biomass in sandy desert ecosystems, they contribute significantly to species richness and diversity and play crucial roles in ecosystem functioning [15]. Within the 0–30 cm layer, ground wind speeds are high and sand particles have strong mobility; herbaceous plants can effectively inhibit sand creep and saltation [16]. Ephemeral and semi-ephemeral herbaceous plants can utilize spring meltwater to rapidly complete their life cycles, playing an important role in spring wind erosion prevention [17]. Even after the growing season when above-ground portions wither, the standing dead material continues to provide wind protection and sand fixation [18]. Plant form is an important factor affecting protective effectiveness, with significant differences in protection efficiency among different forms. This study employs wind tunnel experiments to investigate the wind erosion control effects of three herbaceous plant forms, aiming to reveal differences in wind erosion inhibition among different forms and promote greater attention to plant form selection in sand control and ecological restoration engineering design.

1.1 Experimental Design

The experiments were conducted in the wind tunnel laboratory of the Mosuowan Desert Research Station, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. The wind tunnel is a DC blowing low-speed type with a total length of 16.2 m, consisting of a power section, stabilization section, contraction section, and test section. The test section measures 1.3 m in length and can accommodate a sand tray. The tunnel features a diffuser side-wall structure with airflow stability coefficient below 1%, turbulence intensity less than 1.5%, and lateral uniformity within $\pm1.5^{-1}$, with a boundary layer thickness of approximately 15 cm [20].

Various herbaceous plants with different growth forms are widely distributed around the research station, predominantly creeping, plexiform, and globular forms. Creeping forms include *Tribulus terrestris*, *Capparis himalayensis*, and *Cynodon dactylon*; plexiform forms include *Karelinia caspia*, *Suaeda glauca*, and *Acroptilon repens*; and globular forms include *Ceratocarpus arenarius*, *Agriophyllum squarrosum*, and *Salsola tragus*. These species exhibit strong drought and heat tolerance. We selected *Tribulus terrestris*, *Karelinia caspia*, and *Ceratocarpus arenarius* as reference species for each form. Plant height and crown width were measured to calculate average values for modeling. Due to significant size differences among forms, different scale ratios were applied based on measured dimensions and wind tunnel boundary layer thickness (approximately 15 cm): 1:6.5 for creeping, 1:5 for plexiform, and 1:4.5 for globular forms (Fig. 1). After scaling, the crown widths were 10 cm for creeping, 12 cm for plexiform, and 14 cm for globular models. The creeping form was only measured for crown width due to its ground-hugging growth habit. Creeping and plexiform models were processed from purchased plastic grass, while globular models used natural *Ceratocarpus arenarius*.

Coverage was calculated as the percentage of vertical projection area of all canopy layers and branches relative to the statistical area. Individual experimental plant models were photographed vertically, and ImageJ software was used to calculate the vertical projection coverage area of branches and leaves for each model, from which individual model coverage was derived (height differences among forms were temporarily ignored). The number of models required for different coverage levels (25%, 30%, 35%, 40%, and 45%) was calculated accordingly. Models were uniformly arranged in rows on a sand tray measuring 87.5 cm × 80 cm × 5 cm, which was placed at the center of the wind tunnel test section floor with its long side parallel to the tunnel walls. The tray was filled with dry natural sand.

According to literature, wind speeds of 7–8 $m \cdot s^{-1}$ can cause damage to plants during vigorous growth stages [21]. Therefore, an intermediate wind speed of 8 $m \cdot s^{-1}$ was selected for the clear wind erosion experiments, with a duration of 3 minutes. Before and after each experimental setup, the sand tray was weighed using an electronic balance. After the wind erosion experiment, the sand tray model was reconfigured and the sand surface was fixed with a sand-fixing agent. Wind speeds at 10 cm and 15 cm heights above the sand tray center were measured using a pitot tube, with data transmitted through a micro-differential pressure transmitter to a data acquisition system for calculation and storage.

1.2 Analysis Methods

Based on the research of Dong Zhibao et al. [22] and considering the experimental conditions, wind speed changes between 10–15 cm can represent the characteristics of the entire vegetation layer. Therefore, wind speeds at 10 cm (U_{10}) and 15 cm (U_{15}) heights were selected to calculate the aerodynamic roughness (Z_0) of different plant form surfaces:

$$Z_0 = \exp\left[\frac{U_{15}\ln(10) - U_{10}\ln(15)}{U_{15} - U_{10}}\right]$$

where U_{10} and U_{15} are wind speeds at 10 cm and 15 cm heights, respectively.

The wind erosion rate (P) refers to the mass reduction of sand per unit time and unit area:

$$P = \frac{M_1 - M_2}{S \times T}$$

where P is the wind erosion rate ($g \cdot m^{-2} \cdot min^{-1}$), M_1 is the initial sand tray weight (g), M_2 is the final sand tray weight (g), S is the sand tray surface area (m^2), and T is the wind erosion duration (min).

The wind erosion inhibition efficiency (K) is the ratio of the difference between the wind erosion amount of the blank control (F_0) and that under different coverage (F), divided by the wind erosion amount of the blank control (F_0):

$$K = \frac{F_0 - F}{F_0} \times 100\%$$

where K is the wind erosion inhibition efficiency (%), F_0 is the wind erosion amount of the blank control (g), and F is the wind erosion amount under different coverage (g).

2.1 Wind Field and Aerodynamic Roughness

Under the indicated wind speed of 8 $m \cdot s^{-1}$, the surface airflow field over sand trays with different plant forms showed substantial changes compared to the empty field (Fig. 3). Below 10 cm height, wind speed was generally reduced, while above 10 cm it increased to some extent. Creeping plants had lower height and thus less influence on the wind field; wind speed increased continuously with height until stabilizing. Plexiform and globular plants had greater heights, and within the plant height range (10 cm), wind speed attenuation was significant, resulting in more chaotic profiles that gradually recovered above 10 cm.

Aerodynamic roughness is an important parameter reflecting the effect of the underlying surface on wind speed. As shown in Fig. 4, aerodynamic roughness increased gradually with coverage, particularly rapidly for plexiform and globular forms. Creeping plants had smaller roughness due to their ground-hugging growth habit and decreasing frictional resistance with height. Under the same vegetation coverage, plexiform plants had the greatest roughness, followed by globular, with creeping plants having the smallest. Roughness increased linearly with vegetation coverage ($R^2 > 0.87$), with a significant relationship ($P < 0.02$). The increasing rates, as indicated by trend line slopes, were: plexiform > globular > creeping (Fig. 4), consistent with results from wind tunnel experiments by Dong et al. [22].

2.2 Wind Erosion Rate Analysis

The wind erosion rate (wind erosion amount per unit time and area) of all three plant forms decreased linearly with increasing coverage, with correlation coefficients $R^2 > 0.87$ and significant relationships ($P < 0.02$). From the fitted trend line slopes (plexiform > globular > creeping), lower coverage resulted in greater differences among the three forms, while higher coverage reduced these differences. At 25% coverage, the creeping form had a wind erosion rate of only $0.48\ g \cdot m^{-2} \cdot min^{-1}$, while globular and plexiform rates were $0.72\ g \cdot m^{-2} \cdot min^{-1}$ and $0.62\ g \cdot m^{-2} \cdot min^{-1}$, respectively. Under the same vegetation coverage, plexiform plants had higher wind erosion rates than globular and creeping forms. At 35% coverage, globular and creeping erosion rates were very close ($0.73\ g \cdot m^{-2} \cdot min^{-1}$ and $0.71\ g \cdot m^{-2} \cdot min^{-1}$, respectively). At 40% coverage, creeping exceeded globular, while at 45% coverage, globular exceeded creeping.

2.3 Wind Erosion Inhibition Efficiency

The wind erosion inhibition efficiency of all three plant forms increased linearly with coverage, showing significant correlations ($P < 0.02$). At 25% coverage, all forms exhibited certain inhibition efficiencies, with globular at 46.11% and creeping at 44.10%, while plexiform was only 20.48%. At 40% coverage, inhibition efficiency increased rapidly for all forms: creeping reached 71.54%, globular 63.20%, and plexiform 56.94%. From the trend line slopes (creeping > globular > plexiform), greater coverage resulted in smaller differences between plexiform and the other two forms, while lower coverage amplified differences. Creeping and globular forms showed relatively small differences, particularly minimal at 40% coverage (difference of 1.85%). With increasing coverage, the difference between creeping and globular changed: globular exceeded creeping below 35% coverage, while creeping exceeded globular above 40% coverage.

These results indicate that the wind erosion inhibition efficiency of all three forms increased linearly with coverage, but significant differences existed among forms at the same coverage. As shown in Fig. 7, at low coverage, the variation coefficient of wind erosion inhibition efficiency among the three forms was relatively large, decreasing linearly with increasing coverage. The relationship between coverage and variation coefficient was significantly negative ($P < 0.003$).

3.1 Differences in Sand Fixation Ability Among Plant Forms

Plants are important components of the underlying surface and play a significant role in regulating land surface processes [23], particularly for soil and water conservation and sandy desertification control in arid regions. Improving vegetation conditions to prevent wind erosion is an important technical approach for sandy desertification control, with vegetation coverage being the most commonly used indicator [24,25]. Scholars typically classify vegetation coverage into low (5%–15%), medium (15%–25%), and high (25%–45%) levels [26], with semi-fixed and fixed sand dunes having coverage ranges of 25%–45% [27]. Our experimental coverage range of 25%–45% encompasses these categories.

The differences in sand fixation ability among the three forms are closely related to their inherent growth habits. Both wind erosion rate and inhibition efficiency varied with coverage, with greater differences at lower coverage and smaller differences at higher coverage. Under the same coverage, globular and creeping forms had very similar wind erosion rates at 35% coverage. At 40% coverage, creeping exceeded globular, while at 45% coverage, globular exceeded creeping. Plexiform forms consistently had higher wind erosion rates than both globular and creeping forms. At low coverage, differences in wind erosion inhibition efficiency among forms were substantial. For example, at 30% coverage, creeping and globular plants achieved inhibition efficiencies of 47.55% and 55.70%, respectively, approaching the efficiencies of plexiform plants at 40% (48.46%) and 45% (56.94%) coverage. Therefore, globular and creeping plant forms have relatively higher sand fixation capacity, while plexiform forms have relatively lower capacity. Plant forms with higher wind erosion inhibition efficiency can achieve sand fixation effects equivalent to those with lower efficiency at higher coverage conditions.

The relationship between globular and creeping forms' inhibition efficiency varies with coverage: globular exceeds creeping below 35% coverage, they are similar above 35%, and creeping exceeds globular below 30% coverage. This may relate to wind erosion effects within the globular plant canopy. At coverage below 35%, globular plants accumulate sand in the canopy wind shadow area [28], but the space between canopy bottom and ground has weak airflow reduction capacity. As coverage increases and plant spacing decreases, the "venturi effect" may create local wind erosion between plants [29], partially reducing wind shadow accumulation.

3.2 Analysis of Reasons for Differences in Sand Fixation Ability

This wind tunnel simulation study demonstrates that all three plant forms showed similar trends in aerodynamic roughness changes, increasing with coverage. Plexiform and globular forms consistently had higher roughness than creeping forms, with different degrees of wind speed reduction but within similar ranges. Wind erosion inhibition efficiency differed significantly among forms and varied with coverage. Globular plants have dense branches and leaves with small porosity coefficients, effectively reducing surface wind speed, particularly in wind shadow zones where large reductions occurred and sand accumulation formed. Plexiform plants have sparse branches that sway in the wind, resulting in weaker surface wind speed reduction and substantially lower wind erosion inhibition capacity. These differences between plexiform and globular forms are consistent with the wind prevention and sand resistance effects of *Artemisia sphaerocephala* and *A. ordosica* studied by Ma Quanlin et al. [30]. For creeping plants, although their low height resulted in weaker near-surface wind speed reduction, their branches grew close to the ground, effectively blocking contact between airflow and sand particles, reducing sand supply and resulting in lower wind erosion amounts. This finding aligns with conclusions by Wang Hansheng et al. [31].

The comparison of wind erosion inhibition efficiency between globular and creeping forms varied with coverage: globular exceeded creeping below 35% coverage, they were similar above 35%, and creeping exceeded globular below 30% coverage. This may relate to wind erosion effects within the globular plant canopy. At coverage below 35%, globular plants accumulated sand in canopy wind shadow areas [28], but the space between canopy bottom and ground had weak airflow reduction capacity. As coverage increased and plant spacing decreased, the "venturi effect" could create local wind erosion between plants [29], partially reducing wind shadow accumulation.

In summary, creeping plants have flexible branches extending outward and clinging to the ground, effectively isolating direct wind-sand interaction. The ground is sheltered by plant branches, experiencing less wind force and maintaining higher wind erosion inhibition efficiency. Globular plants have dense canopies and strong stems with small porosity coefficients, providing good sand fixation capacity. Plexiform plants have relatively sparse and soft branches that swing significantly in wind, resulting in weaker sand-blocking and fixation capacity. Therefore, from a sand fixation perspective, creeping and globular forms are more suitable for biological sand control engineering; from a sand burial resistance perspective, plexiform and globular plants are more appropriate for areas with abundant external sand sources.

4 Conclusions

Herbaceous plants play important roles in biological sand control engineering. Below plant height, surface wind speed of all three forms was reduced. With increasing coverage, roughness increased linearly at rates of: plexiform > globular > creeping. Both wind erosion rate and inhibition efficiency varied with coverage, with greater differences at lower coverage and smaller differences at higher coverage. Overall, plexiform plants had relatively lower wind erosion inhibition efficiency, while globular and creeping forms had higher efficiency. The difference between globular and creeping varied with coverage: globular exceeded creeping below 35% coverage, while creeping exceeded globular above 40% coverage.

Differences in sand fixation capacity among the three forms were closely related to their growth characteristics. Globular and creeping forms have relatively low growth heights and high branch density; airflow passing through experiences blocking and friction, substantially reducing wind kinetic energy and sand-carrying capacity, resulting in relatively high sand fixation capacity. Plexiform plants have relatively soft and sparse branches that swing in wind, providing poor effects on wind-sand activity, thus having relatively low sand fixation capacity. The differences between plexiform and globular forms are consistent with results from Ma Quanlin et al.' s [30] study on *Artemisia sphaerocephala* and *A. ordosica*. For creeping forms, although low height resulted in weaker near-surface wind speed reduction, branches growing close to the ground effectively blocked contact between airflow and sand particles, reducing sand supply and wind erosion amounts, consistent with conclusions by Wang Hansheng et al. [31].

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