Numerical Simulation of the Influence of Typical Plant Architecture of Desert Shrubs on Aeolian Sand Flow Field: Postprint

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Date: 2023-05-30T00:00:00+00:00

Abstract

This study investigates the flow field distribution around desert shrubs with typical plant architectures, aiming to provide a theoretical basis for the rational selection of windbreak and sand-fixation vegetation with different plant forms in arid and semi-arid regions. This paper uses FLUENT software to conduct numerical simulations of the flow field around shrubs with three typical plant architectures (urn-shaped, fusiform, and broom-shaped), analyzes the influence of different plant morphologies on wind-sand flow, and validates the results through wind tunnel experiments. The results indicate: (1) The flow field around the three plant architectures can be divided into five zones, with three vortices present behind each plant. Influenced by vortex intensity, during the initial stage of sand accumulation, fusiform and broom-shaped plants primarily accumulate sand at 6–7 H behind the plant, whereas urn-shaped plants accumulate sand near 3 H. (2) Influenced by the height layer of the plant's maximum side area, the minimum wind speed at 1 H behind the shrubs of the three architectures occurs at heights of 0.3 m, 0.4 m, and 0.8 m, respectively, with optimal protection heights of 0.2–0.4 m, 0.3–0.6 m, and 0.8–1 m, respectively. The aerodynamic roughness behind the three plant architectures decreases progressively, with the roughness of the urn-shaped architecture being significantly higher than that of the other architectures. (3) All three plant architectures can effectively reduce wind speed within the range of −2 to 10 H. The wind protection effectiveness in the near-surface region behind the plants follows the order urn-shaped > fusiform > broom-shaped, whereas the wind protection effectiveness in the mid-to-high altitude region decreases with increasing plant spacing. (4) At T=10 s, the total sand accumulation lengths around the three plant types are 8.5 H, 6H, and 4.5 H, respectively. Haloxylon ammodendron and Calligonum mongolicum exhibit varying degrees of wind erosion at distances of 5–5.5 m and 4.5–6 m from the inlet, respectively. Compared with other plants, Nitrariasphaerocarpa demonstrates superior sand-blocking effectiveness. It is

recommended that in windbreak and sand-fixation projects, it be combined with Haloxylon ammodendron and Calligonum mongolicum, thereby leveraging the sand-blocking function of Nitrariasphaerocarpa while utilizing the better mid-to-high altitude wind protection effects of Haloxylon ammodendron and Calligonum mongolicum.

Full Text

Numerical Simulation of Wind-Sand Flow Field Around Typical Shrub Morphologies in Desert Regions

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Abstract

This study investigates the flow field distribution around typical shrub morphologies in desert regions to provide a theoretical basis for rational selection of windbreak vegetation with different plant forms in arid and semi-arid areas. Using FLUENT software, we conducted numerical simulations of the flow field around three typical shrub morphologies (altar-shaped, shuttle-shaped, and broom-shaped) and analyzed their effects on wind-sand flow, with validation through wind tunnel experiments. The results indicate that: (1) The flow field around each shrub morphology can be divided into five distinct zones, with two vortices forming behind each plant. Due to differences in vortex intensity, shuttle-shaped and broom-shaped shrubs accumulate sand primarily 6–7 H behind the plant during the initial accumulation stage, whereas altar-shaped shrubs accumulate sand near 3 H. (2) Influenced by the height layer of maximum side-profile area, the minimum wind speed values at 1 H behind the three shrub types occur at heights of 0.3 m, 0.4 m, and 0.8 m, respectively, with optimal protection heights of 0.2–0.4 m, 0.3–0.6 m, and 0.8–1 m. The aerodynamic roughness decreases gradually for all three types, with the altar-shaped shrub exhibiting significantly higher roughness than the other two morphologies. (3) All three shrub types effectively reduce wind speed within the range of -2 H to 10 H. Near-surface wind protection benefits follow the order: altar-shaped > shuttle-shaped > broom-shaped, while mid-to-high altitude protection benefits decrease with increasing plant spacing. (4) At T = 10 s, Haloxylon ammodendron and Calligonum mongolicum exhibit varying degrees of wind erosion at distances of 5–5.5 m and 4.5–6 m from the inlet, respectively. Compared with other species, Nitraria sphaerocarpa demonstrates superior sand-blocking effects. Therefore, we recommend combining N. sphaerocarpa with H. ammodendron and C. mongolicum in windbreak and sand fixation projects to leverage both the sand-blocking capacity of N. sphaerocarpa and the effective mid-to-high altitude wind reduction of H. ammodendron and C. mongolicum.

Keywords: desert shrub; plant morphology; windbreak and sand fixation; numerical simulation

1. Introduction

Vegetation protects the land surface, and increasing vegetation coverage is the primary means of wind erosion control. However, in arid and semi-arid regions, water limitations result in vegetation dominated by low-coverage xerophytic shrubs that often exist as individual plants or clusters. Research on their relationship with wind erosion can thus be simplified to the windbreak and sand fixation effects of single shrubs. Different shrub types exhibit varying effects on surrounding airflow fields, making it crucial to study wind speed and sediment transport characteristics around individual plants of different morphologies. Such research is essential for rational vegetation selection in wind erosion control and provides valuable guidance for designing sparse shrub shelterbelt projects with different configurations.

Current research on plant morphology and wind erosion employs two main approaches. The first uses traditional wind tunnel or field experiments to investigate morphological differences. For instance, Kang Liqiang et al. measured the effects of slender and top-heavy plant shapes on aerodynamic roughness through wind tunnel experiments, while Abbas et al. studied two plant forms and found that Ligustrum lucidum showed greater wind resistance than Cosmos bipinnatus. These studies primarily focused on single-plant effects on wind fields but paid less attention to sand particle movement and sediment transport characteristics around plants.

The second approach uses numerical simulation to examine flow field changes around individual vegetation elements. Compared with field or wind tunnel experiments, numerical simulation offers clear advantages in data acquisition and workload. Li Zhengnong et al. simplified Buxus sinica into a symmetrical model to effectively simulate tree effects on wind fields, while other researchers used FLUENT software to study flow fields around single plants of different shapes, concluding that bottom-heavy, top-light plants provide better wind protection. These studies enhanced understanding of how plant morphology affects windbreak efficiency, but existing numerical simulations of individual vegetation elements have focused more on tall trees, with limited research on shrubs and different shrub morphologies regarding wind speed and sediment transport characteristics.

Desert shrubs play a vital role in sandy desert ecosystems, maintaining ecological stability in arid and semi-arid regions. With well-developed root systems and strong vitality, these shrubs exhibit dense foliage during the growing season, effectively reducing wind momentum and providing windbreak and sand-blocking functions. Vegetation morphology and structure are key parameters controlling wind erosion, with different shrub morphologies showing significant differences in windbreak and sand-blocking benefits. This study employs numerical simulation to investigate three typical desert shrub morphologies, analyzing variations in wind speed, aerodynamic roughness, and sand volume fraction before and after different shrub types. By comparing the windbreak and sand fixation benefits of different vegetation forms and validating results with existing wind tunnel experiments, we aim to reveal differences in how plant morphology affects wind-sand flow activity, promote attention to shrub morphology in windbreak and sand fixation project design in arid and semi-arid regions, and provide references for rational selection of windbreak vegetation with different morphologies.

1.1 Study Area and Target Species

The study area is located in the northeastern Ulan Buh Desert, where various desert shrubs grow, predominantly altar-shaped, shuttle-shaped, and broom-shaped forms. Common species include *Nitraria sphaerocarpa*, *Caragana korshinskii*, *Sarcozygium xanthoxylon*, *Hedysarum mongolicum*, *Calligonum mongolicum*, *Haloxylon ammodendron*, and *Hedysarum scoparium*. Based on comparative analysis, we selected *Nitraria sphaerocarpa*, *Haloxylon ammodendron*, and *Calligonum mongolicum* as representatives of three typical morphologies. Simulation parameters were derived from existing field surveys conducted during the growing season. In uniformly distributed shrub areas, we established 100 m × 100 m plots, selected approximately 100 shrubs of similar age, recorded height and crown width parameters, and calculated average values as reference data for the three morphology models (Table 1).

Table 1 Field survey results

Plant Type	Height (m)	Crown Width (m)	Height Layer of Max Side-Profile Area (m)	Plant Side-Profile Porosity
Nitraria sphaerocarpa	0.50	1.20	0.10–0.30	0.106–0.828
Haloxylon ammodendron	1.20	1.00	0.30–0.60	0.906–0.718
Calligonum mongolicum	1.50	1.10	0.60–1.00	0.940–0.578

This study investigates two-dimensional flow field characteristics around shrubs.

For modeling convenience, we processed plant height and crown width data through averaging and integerization. Based on trial calculations and simulations, model vegetation parameters were determined (Table 2). As shown in Table 2, *Nitraria sphaerocarpa* exhibits maximum side-profile area at 0.10–0.30 m, presenting a bottom-heavy, top-narrow altar shape with low branch height, low center of gravity, and overall proximity to the ground. *Haloxylon ammodendron* displays a shuttle shape that is wide in the middle and narrow at both ends, relatively tall, with its center of gravity at mid-plant. *Calligonum mongolicum* has the greatest branch height, with maximum side-profile area in the upper plant region, presenting a broom shape with high center of gravity.

Table 2 Model plant parameters

Plant Type	Height (m)	Windward Crown Width (m)	Height Layer of Max Side-Profile Area (m)	Plant Side-Profile Porosity
Nitraria sphaerocarpa	0.5	1.2	0.10–0.30	0.106–0.828
Haloxylon ammodendron	1.2	1.0	0.30–0.60	0.906–0.718
Calligonum mongolicum	1.5	1.1	0.60–1.00	0.940–0.578

1.2 Numerical Simulation Methods

1.2.1 Plant Modeling Since drag and gravity forces on sand particles in wind-sand flow essentially act within the same plane, this study employs a two-dimensional simplified model. Based on Table 2 and previous modeling experience, we utilized AutoCAD software to establish porous geometric models of *Nitraria sphaerocarpa*, *Haloxylon ammodendron*, and *Calligonum mongolicum*, corresponding to altar, shuttle, and broom shapes, respectively. The simplified plant models approximate and generalize actual plant morphology, using relatively low porosity and various measured vegetation characteristic parameters to represent shrub forms during the growing season, thus ensuring simulation reliability.

The flow field length was set at 20 H, with a computational height of 10 H. The simplified plant model was positioned 5 H from the inlet, sand bed thickness was 0.05 m, and the computational domain is illustrated in Figure 1. Due to the regular model shapes, we employed quadrilateral grids with structured meshing. Since this study focuses on flow field characteristics of sand particles and interactions between sand particles and the sand bed surface before and after plants, we refined grids near the ground surface and plant areas. After multiple simulations and adjustments, the grid size growth rate was set at 1.05, with total computational domain grids numbering 45,000. The minimum orthogonal quality far exceeded 0.7, and the maximum orthogonal skewness was much less than 0.05, indicating good grid quality that meets computational requirements.

Figure 1 [**Figure 1: see original paper**] Model diagram

1.2.2 Parameter Settings Based on previous simulation parameter settings, this study treated wind-sand flow as an incompressible fluid. The model left inlet adopted velocity boundary conditions, the right side used pressure outlet boundary conditions, the upper wall employed symmetric boundaries, and the lower wall and plant model used solid no-slip boundaries. Wind-sand flow particle diameters generally range 0.075–0.25 mm; we set particle diameter at ds = 0.1 mm, sand density at s = 2650 $\text{kg} \cdot \text{m}^{-3}$, initial sand bed packing ratio at $\alpha = 0.02\%$, air density at = 1.225 $\text{kg} \cdot \text{m}^{-3}$, air viscosity at s = 0.047 $\text{Pa} \cdot \text{s}$, and air kinematic viscosity at = 1.7894×10^{-5} $\text{m}^2 \cdot \text{s}^{-1}$.

The inlet boundary velocity followed a typical wind speed profile:

$$u = \frac{u_*}{\kappa} \ln\left(\frac{y}{y_0}\right)$$

where u is wind speed at height y ($\text{m} \cdot \text{s}^{-1}$), u_* is friction velocity ($\text{m} \cdot \text{s}^{-1}$), is the von Kármán constant (0.4), and y_0 is roughness length (m).

The solution model employed an Eulerian two-fluid model with an additional turbulence model. Due to the need to consider velocity changes in the flow field and solution accuracy issues, we used an unsteady transient solution method for simulation. The flow field solver adopted the Phase Coupled SIMPLE algorithm, with spatial discretization using second-order upwind schemes and time step set at 0.001 s.

1.2.3 Governing Equations This simulation treated airflow as incompressible flow, with governing equations including the continuity equation, momentum equation, and turbulence model equations. Based on simulation requirements, we selected the standard k- model suitable for high Reynolds numbers.

The continuity equation is:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_x)}{\partial x} + \frac{\partial (\rho u_y)}{\partial y} = 0$$

where u and u_y are velocity vectors in two directions,   is density, and t is time (s).

The momentum equation is:

$$\rho\frac{\partial\bar{u}}{\partial t}=-\frac{\partial p}{\partial x}+\frac{\partial\tau_{xx}}{\partial x}+\frac{\partial\tau_{xy}}{\partial y}+\rho g_x$$

$$\rho\frac{\partial\bar{v}}{\partial t}=-\frac{\partial p}{\partial y}+\frac{\partial\tau_{yx}}{\partial x}+\frac{\partial\tau_{yy}}{\partial y}+\rho g_y$$

where p is pressure on fluid micro-elements (Pa), ū is the velocity vector, τ , τ y, τyx, τyy are viscous stress components caused by molecular viscosity (Pa), and g is gravitational acceleration ($\mathrm{m \cdot s^{-2}}$).

The turbulent kinetic energy k and dissipation rate   equations for the standard k- model are:

$$\frac{\partial(\rho k)}{\partial t}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

where _t = C_ $\mathrm{k^2}$/ is turbulent viscosity coefficient, C_ is an empirical constant, G_k represents turbulent kinetic energy caused by mean velocity gradients, G_b represents turbulent kinetic energy caused by buoyancy, σk *= 1.0,* σ = 1.3, C*{1 } = 1.44, C*{2 } = 1.92, and C_ = 0.09.

Aerodynamic roughness is the height where near-surface wind speed reaches zero and represents an important parameter reflecting surface wind impedance, with greater roughness indicating stronger wind-weakening capacity. The calculation formula is:

$$z_0=\exp\left(\frac{u_1\ln z_2-u_2\ln z_1}{u_1-u_2}\right)$$

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

Plant wind protection efficiency is calculated as:

$$\eta_{xz}=\frac{v_z-v_{xz}}{v_z}\times 100\%$$

where _{xz} is wind protection efficiency at distance x and height z (%), x is horizontal distance from the plant (negative for windward side, positive for leeward side), z is height above ground (m), v_{xz} is wind speed at position (x, z) after the plant ($m \cdot s^{-1}$), and v_z is initial wind speed at height z on bare sand ($m \cdot s^{-1}$).

1.3 Analysis Methods

1.4 Wind Tunnel Test Overview

To verify simulation reliability, we used existing wind tunnel test data for validation. The test was conducted at the Desert Forestry Experimental Center of the Chinese Academy of Forestry using a DC open-circuit wind tunnel with 1 m width and height and a 10 m test section. Wind speed was regulated through a frequency converter, with a design wind speed of 6 $m \cdot s^{-1}$ in this study.

Since we primarily used wind tunnel-measured sand-blocking benefits of different shrub morphologies to validate simulation results, we focus here on detailing the experimental setup for measuring sand-blocking benefits. A stepped sand collector measured sediment transport at different height layers. Representative individual shrubs of *Nitraria sphaerocarpa*, *Haloxylon ammodendron*, and *Calligonum mongolicum* were selected from sample plots, with typical plants approximately 1 m tall collected and returned to the test site for precise measurement of vegetation parameters. The three types of individual shrubs were fixed along the wind tunnel centerline, with a 10-layer stepped sand collector placed 1 H behind each plant, each layer having a 2 cm × 2 cm inlet cross-section. To ensure adequate sand supply, a 5 cm thick sand bed was laid in the test section, filtered through a 40-mesh screen. Each shrub type underwent erosion tests at 6 $m \cdot s^{-1}$ for 2 min, repeated three times, with sand replenished and the surface leveled after each test. A blank control group (no vegetation) was also established to measure sediment transport rates for comparison.

Figure 2 [**Figure 2: see original paper**] Distribution of sand transport rate and sand volume fraction with height

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2. Results

2.1 Validation of Wind-Sand Two-Phase Flow Field

To validate the rationality of our wind-sand flow field settings, we compared simulation results with existing wind tunnel test data. Research indicates that sand volume fraction distribution in wind-sand movement is consistent with sediment transport rate distribution. Therefore, we used sediment transport rates at 1 H behind *Nitraria sphaerocarpa* and on bare sand under 6 $m \cdot s^{-1}$ wind speed (friction velocity 0.3752 $m \cdot s^{-1}$) from wind tunnel tests as controls to analyze simulated sand volume fraction distribution with height under the same conditions. As shown in Figure 2, both sediment transport rate and sand volume fraction exhibit similar decreasing trends with height, following a logarithmic reduction pattern that aligns with sand particle transport characteristics and wind-sand flow structure features. This demonstrates high simulation reliability and accurate representation of the flow field around vegetation.

2.2 Flow Field Characteristics Around Shrubs

2.2.1 Comparison of Wind Speed Flow Field Features To compare the effects of the three shrub morphologies on the flow field, we selected a 6 $\mathrm{m \cdot s^{-1}}$ wind speed profile for simulation (all subsequent speeds follow this condition unless otherwise specified), with wind speed at 0.1 m height being 6 $\mathrm{m \cdot s^{-1}}$. Figure 3 shows wind speed distribution for the three shrub types. Under the same inflow conditions, all three plants exhibit acceleration zones above the canopy, deceleration zones on the windward side, and turbulent deceleration zones, vortex acceleration zones, and recovery zones on the leeward side.

Airflow disturbance begins 2–3 H before the plant, forming a deceleration zone because dense branching increases wind-exposed surface area and accelerates wind energy dissipation. When airflow reaches the plant front, some flows converge and rise, forming an acceleration zone above the canopy, while other flows pass through the plant. After vortex action, wind speed drops sharply behind the plant, forming a turbulent deceleration zone—the main protection area whose size directly affects protection effectiveness. With increasing distance behind the plant, wind speed gradually recovers to normal levels, causing the plant to lose its protective capacity. Notably, distinct vortex acceleration zones appear around all plants, with sizes following the order: *Calligonum mongolicum* > *Haloxylon ammodendron* > *Nitraria sphaerocarpa*, corresponding to branch heights of 0.12 m, 0.08 m, and 0.03 m, respectively. The vortex acceleration zone shows a clear increasing trend with branch height, consistent with existing research conclusions.

Figure 3 [**Figure 3: see original paper**] Cloud chart of wind speed around shrubs

2.2.2 Analysis of Vortices Behind Plants Previous studies indicate that the aerodynamic principle of sand prevention involves local wind speed reduction and airflow circulation bubbles (vortex flows). Figure 4 shows wind speed vectors around different shrub types, revealing two main vortices behind the leeward side. Vortex 1 is the primary protection area and is influenced by shrub morphology, with different positions for each type. For *Nitraria sphaerocarpa*, *Haloxylon ammodendron*, and *Calligonum mongolicum*, vortex 1 is located 0.5–3.5 H, 0.5–5 H, and 0.5–5.5 H behind the plant, respectively, while vortex 2 is located at 4–5 H, 6.5–7.5 H, and 6–7 H, respectively.

The formation mechanism involves: airflow passing through the plant is compressed by branches and leaves, and after crossing the plant, the flow cross-section suddenly expands, creating upward and downward 分流. The downward-moving portion lifts near the plant and returns toward it, forming vortex 1—

the main sand accumulation area. Although smaller in form, vortex 2 also has weaker intensity, causing substantial sand deposition. Its formation relates to collisions between the sinking airflow from vortex 1 and airflow from the vortex acceleration zone. Under the influence of vortex 1's tail, airflow is compressed again to form vortex 3.

Sand-blocking capacity directly relates to vortex intensity and scale: larger vortex range and weaker intensity facilitate sand deposition. The vortex 1 ranges follow the order: *Haloxylon ammodendron* > *Calligonum mongolicum* > *Nitraria sphaerocarpa*, while intensities follow: *Calligonum mongolicum* > *Haloxylon ammodendron* > *Nitraria sphaerocarpa*. Although *Haloxylon ammodendron* and *Calligonum mongolicum* have large vortex 1 ranges, their intensities are also strong. Consequently, during initial sand accumulation, sand-laden airflow passing through these plants accumulates primarily 6–7 H behind the plant, whereas *Nitraria sphaerocarpa* accumulates sand near 3 H.

Figure 4 [**Figure 4: see original paper**] Vector diagram of wind speed around shrubs

2.2.3 Comparison of Wind Speed Profiles Behind Plants To further investigate vertical protection effects of the three shrub types, we extracted vertical cross-sections at 1 H behind plants under 6 $\mathrm{m \cdot s^{-1}}$ wind conditions and plotted wind speed profiles against bare sand controls (Figure 5). The three shrub types show distinct differences in wind speed profiles. First, near-surface initial wind speeds differ: *Nitraria sphaerocarpa* shows the lowest initial speed (1.57 $\mathrm{m \cdot s^{-1}}$), while *Haloxylon ammodendron* and *Calligonum mongolicum* both exceed bare sand speed, indicating that *Nitraria sphaerocarpa* has wind erosion resistance at 1 H, whereas the other two may promote wind erosion around plants—a phenomenon warranting further investigation in ecological restoration projects.

Second, protection heights differ significantly: *Nitraria sphaerocarpa*, *Haloxylon ammodendron*, and *Calligonum mongolicum* have protection heights of 1.1 m, 1.5 m, and 1.65 m, respectively, with *Calligonum mongolicum* having the highest protection height corresponding to its plant height.

Further analysis reveals that bare sand wind profiles follow a logarithmic growth pattern, whereas shrub profiles do not form regular logarithmic curves but instead show vertical "S-shaped" trends. The vertical airflow distribution can be divided into low-altitude deceleration zones, vortex zones, and high-altitude acceleration zones, with patterns related to plant morphology. Influenced by branch height, initial wind speed is relatively large, then decreases with height due to plant blockage and factors like sand creep and saltation, forming low-altitude deceleration zones. Vortex zones relate to complex branch structures, creating small-scale turbulence as airflow passes through pores. High-altitude acceleration zones show rapid wind speed increase with height due to plant blockage.

Minimum wind speed values behind the three shrub types occur at heights of 0.3 m, 0.4 m, and 0.8 m, with optimal protection heights of 0.2–0.4 m, 0.3–0.6 m, and 0.8–1 m, respectively. Notably, 0.8 m serves as an important boundary for wind speed development across all types, a phenomenon requiring further investigation.

Figure 5 [**Figure 5: see original paper**] Wind speed profile of a single shrub 1 H later

2.2.4 Analysis of Aerodynamic Roughness Behind Plants As shown in Equation (6), observation height and wind speed selection are critical for calculating aerodynamic roughness. Since wind profile changes at 0.5–2 m can represent entire shrub layer characteristics, we selected wind speed values at 0.5 m and 2 m behind the three shrub types and bare sand, calculating aerodynamic roughness at different distances behind each type (Figure 6).

Figure 6 shows that roughness decreases gradually with distance behind all three types. *Nitraria sphaerocarpa* exhibits maximum roughness at 1 H, with roughness values for *Nitraria sphaerocarpa*, *Haloxylon ammodendron*, and *Calligonum mongolicum* being 5.6, 2.8, and 1.8 times that of bare sand, respectively. *Calligonum mongolicum* shows the smallest roughness. At 10 H, roughness of *Haloxylon ammodendron* and *Calligonum mongolicum* basically equals that of bare sand. The significantly higher roughness of altar-shaped shrubs indicates stronger capacity to weaken near-surface wind forces.

Figure 6 [**Figure 6: see original paper**] Aerodynamic roughness of shrub plants

2.2.5 Analysis of Plant Wind Protection Efficiency We extracted wind speed values at different heights and distances under 6 $\mathrm{m \cdot s^{-1}}$ wind conditions and calculated single-shrub wind protection efficiency using Equation (7). Analysis of Figure 7 shows that horizontal wind protection benefits before the plant increase with decreasing plant distance, particularly intensifying within -2 H to 0 H. Vertical wind protection benefits decrease with height but remain positive, indicating that all shrubs significantly reduce wind speed within their height ranges.

Behind the plant, trends can be divided into near-surface zones (0–0.3 m) and mid-to-high altitude zones (0.3–1.5 m). In near-surface zones, horizontal wind protection efficiency shows wave-like changes with distance; vertical benefits increase with height within 0–0.1 H behind the plant. In mid-to-high altitude zones, vertical protection benefits of *Nitraria sphaerocarpa* and *Haloxylon ammodendron* decrease fluctuatingly with height, while *Calligonum mongolicum* shows fluctuating increases. Horizontal benefits generally decrease with distance, with optimal protection occurring at 2–5 H behind the plant. Using *Calligonum mongolicum* as an example, maximum protection benefits at 0.1 m, 0.3 m, 0.5 m, 0.7 m, and 0.9 m heights are 98.1%, 94.4%, 89.8%, 85.6%, and

82.3%, respectively, all appearing at 3 H.

Further analysis shows that except for negative values at 0.1 m height for *Haloxylon ammodendron* and *Calligonum mongolicum*, all types provide effective protection below their respective heights. However, optimal protection areas differ significantly: *Nitraria sphaerocarpa*'s optimal zone appears at 0.3 m height within 2–5 H; *Haloxylon ammodendron*'s optimal zone appears at 0.5 m height within 2–5 H; and *Calligonum mongolicum*'s optimal zone appears at 0.9 m height within 2–5 H. Overall, all three types effectively reduce wind speed within -2 H to 10 H, but their regional protection benefits differ markedly, with *Nitraria sphaerocarpa* performing best near the surface and *Haloxylon ammodendron* and *Calligonum mongolicum* performing better at medium-to-high altitudes.

Figure 7 [**Figure 7: see original paper**] Protection benefit of shrub plants

2.3 Sediment Transport Characteristics

2.3.1 Analysis of Sediment Transport Before and After Plants When wind speed reaches the threshold for sand movement, surface sand particles begin moving through creep, saltation, and suspension, forming wind-sand flow. Shrubs can intercept and retain sand particles, causing deposition around plants and forming shrub dunes, though sand-blocking capacities differ among morphologies. To investigate sand-blocking effects of the three typical desert shrubs, we extracted sand accumulation cloud diagrams at T = 10 s under 6 $\mathrm{m \cdot s^{-1}}$ wind conditions.

- Nitraria sphaerocarpa* shows minimal sand accumulation on the windward slope initially, with most sand depositing on the leeward slope at a certain distance from the plant. Over time, leeward deposition points gradually move toward the plant. At T = 10 s, leeward deposition extends from 3 H to the plant base, with leeward accumulation length increasing from 4.5 H to 8.5 H and total accumulation length reaching 8.5 H.

Haloxylon ammodendron shows minimal windward accumulation concentrated near the plant, with greater leeward accumulation that also moves closer to the plant over time. At T = 10 s, leeward deposition extends from 6 H to 2.5 H, with total accumulation length of 6 H and maximum accumulation height of 0.18 m.

Calligonum mongolicum shows the least windward accumulation. At T = 5 s, leeward deposition occurs at 6 H, increasing to 2.5 H by T = 10 s, with total accumulation length of 4.5 H and height increase of 0.08 m, indicating relatively poor sand-blocking benefits compared to other types.

Figure 8 [**Figure 8: see original paper**] Sand accumulation cloud atlas around shrubs

2.3.2 Analysis of Surface Erosion and Deposition Under 6 $\mathrm{m \cdot s^{-1}}$ wind conditions, airflow-sand bed interactions cause sand particles to rearrange through various movement forms, changing sand bed packing ratios. While difficult to detect precisely in practice, numerical simulation can address this challenge. To investigate erosion and deposition patterns around different shrub morphologies, we initially set a uniform 5 cm thick sand bed with single particle size and initial packing ratio of 0.02, extracting sand bed packing ratios at T = 10 s along the flow path to reflect morphology effects on regional erosion and deposition.

Based on wind-sand transport patterns and previous research, we propose: if sand volume fraction in the 0–0.05 m height layer remains below 0.05 cm^{-3} while that above 0.05 m stays near 0.05 cm^{-3}, the area experiences wind erosion; if sand volume fraction in the 0–0.05 m layer exceeds 0.05 cm^{-3} while that above 0.05 m remains near 0.05 cm^{-3}, the area shows deposition.

Figure 9 clearly shows that wind-sand flow affected by *Nitraria sphaerocarpa* maintains sand volume fraction below 0.05 cm^{-3} in the 0–0.05 m layer but near 0.05 cm^{-3} above 0.05 m at about 4.5 m from the inlet, indicating wind erosion. Around *Nitraria sphaerocarpa*, slight disturbances occur in sand bed packing ratios above 0.05 cm height, but values remain above 0.02, indicating deposition. Downwind, weak erosion and deposition zones form under vortex influence.

Haloxylon ammodendron and *Calligonum mongolicum* also show some windward deposition, but unlike *Nitraria sphaerocarpa*, they exhibit wind erosion beneath the plant or immediately behind it. Although high-altitude sand accumulation increases, sand volume fractions below 0.04 m for *Haloxylon ammodendron* and below 0.05 m for *Calligonum mongolicum* drop below 0.02 cm^{-3}, indicating erosion at 4.5–6 m and 5–5.5 m from the inlet, respectively. After passing the plants, both species show deposition at 6–10 m and 6–9 m behind the plants, respectively.

Overall, the three shrub types significantly affect surface erosion and deposition microtopography, with varying degrees of deposition before and after plants. However, except for *Nitraria sphaerocarpa*, the other two species show wind erosion around plants, related to their greater branch heights.

Figure 9 [**Figure 9: see original paper**] Erosion around shrubs

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3. Discussion

3.1 Causes of Wind Protection Capacity Differences

Morphological differences among desert shrubs represent adaptive strategies to spatial, light, and water resources. Environmental conditions affect plant morphology development, which in turn influences windbreak and sand fixation benefits. Our simulations show that the flow field around individual shrubs can be divided into five zones: deceleration, above-canopy acceleration, turbulent deceleration, vortex acceleration, and recovery zones. Vortex acceleration zone formation correlates with branch height, with greater branch heights creating "venturi effects" that significantly affect nearby flow fields.

All shrub types exhibit two vortices behind them, with intensity differences affecting sand deposition locations. Altar-shaped shrubs have dense foliage with small windward porosity coefficients, resulting in weaker vortex 1 intensity, greater wind speed reduction in wind shadow areas, and wind shadow accumulation. Thus, during initial sand accumulation, *Nitraria sphaerocarpa* accumulates sand near 3 H, while shuttle-shaped and broom-shaped shrubs with sparse lower foliage and large porosity experience airflow acceleration through plant pores, forming stronger vortex 1. Consequently, they initially accumulate sand at 6–7 H.

Wind speed profiles at 1 H behind the three shrub types show vertical S-shaped trends, with airflow vertically distributed into low-altitude deceleration, vortex, and high-altitude acceleration zones related to plant morphology. Minimum wind speeds occur at 0.3 m, 0.4 m, and 0.8 m behind the three types, with optimal protection heights of 0.2–0.4 m, 0.3–0.6 m, and 0.8–1 m, respectively. Wind protection effects depend on windward side-profile area size, which is determined by plant morphology, thereby affecting protection range and optimal height.

Nitraria sphaerocarpa has a low, altar-shaped form with dense lower branches and maximum side-profile area at 0.1–0.3 m, effectively reducing near-surface wind speeds with optimal protection at 0.2–0.4 m. *Haloxylon ammodendron* has a shuttle shape with moderate branch height, creating a vortex acceleration zone at the base that increases local wind speed, but its large windward side-profile area with maximum at 0.3–0.6 m provides good wind protection with optimal height at mid-plant. *Calligonum mongolicum* has a broom shape with large branch height, weak near-surface wind protection, and potential root zone erosion, but its tall form with maximum side-profile area at 0.6–1.0 m provides good protection above 0.6 m, with optimal protection at 0.8–1 m.

Overall, wind protection capacities differ significantly among morphologies. Altar-shaped shrubs with dense foliage and large lower side-profile areas effectively reduce near-surface wind speeds, while shuttle-shaped and broom-shaped shrubs, though sparse at the base and prone to "venturi effects," provide good mid-to-high altitude wind protection due to their tall forms and small mid-to-upper canopy porosity coefficients.

3.2 Causes of Sand-Blocking Capacity Differences

Sand-blocking capacities follow the order: *Nitraria sphaerocarpa* > *Haloxylon ammodendron* > *Calligonum mongolicum*, with total sand accumulation lengths of 8.5 H, 6 H, and 4.5 H, respectively. Plant morphology also affects sand-blocking capacity, with hemispherical crowns showing greater sand interception than conical or shuttle shapes. *Nitraria sphaerocarpa* has the largest sand accumulation range, while *Haloxylon ammodendron* and *Calligonum mongolicum* show obvious wind erosion zones, making *Nitraria sphaerocarpa* superior for windbreak and sand fixation—consistent with existing experimental results.

The reason is that wind-sand activity primarily occurs near the surface (0–0.3 m). *Nitraria sphaerocarpa* grows close to the ground with a bottom-heavy, top-narrow altar shape and dense lower branch structure that clearly blocks sand particles, reducing those crossing or passing through the plant and providing excellent sand-blocking effects consistent with its dune-forming characteristics. All three shrub types show higher leeward than windward sand accumulation because of differential wind-sand flow reduction capacity. When wind-sand flow reaches the plant, windward speed decreases but most airflow is forced upward, converting some kinetic energy to gravitational potential energy and losing additional kinetic energy through collisions with internal plant structures, further reducing sand-carrying capacity and causing more sand to accumulate on the leeward slope.

In practical windbreak and sand fixation engineering, while considering individual plant protection benefits, we must also account for group protection effects and mechanisms of shrub belts. Rational shrub configuration can achieve effective wind erosion control under limited water conditions. Numerical simulation of individual plant flow fields aims to design more effective sparse shrub shelterbelts. Previous studies found optimal spacing of 2.5–3 H for *Artemisia sphaerocephala* shelterbelts and 1–1.5 H for willow windbreaks. This study found optimal protection heights of 0.2–0.4 m, 0.3–0.6 m, and 0.8–1 m for the three shrub types, with sand-blocking capacities following the order: *Nitraria sphaerocarpa* > *Haloxylon ammodendron* > *Calligonum mongolicum*. Therefore, we recommend combining *Nitraria sphaerocarpa* with *Haloxylon ammodendron* and *Calligonum mongolicum* in practice to leverage both the superior sand-blocking capacity of *Nitraria sphaerocarpa* and the effective mid-to-high altitude wind reduction of *Haloxylon ammodendron* and *Calligonum mongolicum*.

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4. Conclusion

Using an Eulerian two-fluid unsteady model, we studied wind-sand flow fields around three typical desert shrub morphologies and validated flow field rationality through wind tunnel tests, reaching the following conclusions:

1. The flow field around individual shrubs can be divided into five zones, with vortex acceleration zones increasing in size with branch height. Two vortices appear behind all plants, but intensity differences cause shuttle-shaped and broom-shaped shrubs to accumulate sand primarily at 6–7 H, while altar-shaped shrubs accumulate sand near 3 H during initial accumulation stages.

2. Influenced by maximum side-profile area height layers, minimum wind

speeds behind the three shrub types occur at 0.3 m, 0.4 m, and 0.8 m, with optimal protection heights of 0.2–0.4 m, 0.3–0.6 m, and 0.8–1 m, respectively. Aerodynamic roughness decreases gradually behind all types, with altar-shaped shrubs showing significantly higher roughness than other morphologies.

3. All three shrub types effectively reduce wind speed within -2 H to 10 H. Near-surface wind protection benefits follow the order: altar-shaped > shuttle-shaped > broom-shaped, while mid-to-high altitude benefits decrease with increasing plant spacing. Optimal protection zones differ markedly among types: altar-shaped shrubs perform best at 0.1–0.3 m height within 2–5 H; shuttle-shaped shrubs at 0.3–0.6 m height within 2–5 H; and broom-shaped shrubs at 0.6–1 m height within 2–5 H.
4. At T = 10 s, all three shrub types show some deposition before and after plants, but *Haloxylon ammodendron* and *Calligonum mongolicum* exhibit wind erosion at 4.5–6 m and 5–5.5 m from the inlet, respectively, related to their large branch heights. *Nitraria sphaerocarpa* demonstrates the best sand-blocking effect. We recommend combining it with *Haloxylon ammodendron* and *Calligonum mongolicum* in windbreak and sand fixation projects to integrate superior sand-blocking with effective mid-to-high altitude wind reduction.

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