Postprint: Numerical Simulation Study on the Effects of Dry Alhagi sparsifolia on Wind-Sand Flow Field

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Abstract

Plant sand fixation is one of the important measures for preventing and controlling wind-sand disasters in desert areas, and camelthorn (Alhagi camelorum), as a typical desert plant, possesses significant application value. Using Fluent software, numerical simulation of the flow field near 30-cm-high dried camelthorn was conducted to analyze wind speed characteristics and sand accumulation characteristics, which were verified through field experiments. The results indicate: (1) The flow field near the plant can be roughly divided into a blocked deceleration zone, an uplift acceleration zone, a turbulent deceleration zone, and a recovery zone. A weak vortex forms behind the plant, and the height of the vortex recirculation zone is related to the distance from the plant, but remains below 0.14 m overall. (2) When the wind speed is 6 m s -1, the plant mainly influences the horizontal wind speed below a height of 0.6 m. Within a certain distance behind the plant, the horizontal wind speed no longer exhibits a strict logarithmic distribution with increasing height, but rather shows two minimum values, and increases rapidly with relatively large acceleration within the height range of 0.3~0.6 m. (3) The windbreak efficiency of the plant overall demonstrates a decreasing trend with increasing wind speed, and this phenomenon becomes more pronounced with increasing height. When the wind speed increases from 6 m s -1 to 10 m s -1, the windbreak efficiency at a height of 0.3 m within 5.3 m behind the plant decreases from 40% to 16.56%. (4) Sand accumulation near the plant varies with wind speed; when wind speed is low, sand accumulation is mainly concentrated near the front of the plant and between plants, and as wind speed increases, sand accumulation shifts backward.

Full Text

Numerical Simulation Study on the Influence of Dry Alhagi camelorum on Wind-Sand Flow Field

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Abstract

Plant sand fixation represents one of the crucial measures for preventing and controlling wind-sand disasters in desert regions, with *Alhagi camelorum* serving as a typical desert plant of significant application value. This study employs numerical simulation to investigate the flow field around 30 cm tall dry *Alhagi camelorum* plants, analyzing wind speed characteristics and sand accumulation patterns, with validation through field experiments. The results indicate: (1) The flow field near the plant can be broadly divided into four zones: blocked deceleration zone, lifting acceleration zone, turbulent deceleration zone, and recovery zone. A weak vortex forms behind the plant, with the height of the recirculation region related to the distance from the plant but generally remaining below 0.14 m. (2) At a wind speed of 6 $\mathrm{m \cdot s^{-1}}$, the 30 cm plant primarily affects horizontal wind speeds below 0.6 m height. The horizontal wind speed at a certain distance behind the plant no longer follows a strict logarithmic distribution with height, but instead exhibits two minima, with wind speed increasing rapidly within the 0.3–0.6 m height range. (3) The plant' s wind protection efficiency generally decreases with increasing wind speed, a phenomenon that becomes more pronounced at greater heights. As wind speed increases from 6 $\mathrm{m \cdot s^{-1}}$ to 10 $\mathrm{m \cdot s^{-1}}$, the wind protection efficiency at 0.3 m height within 5.3 m behind the plant decreases from 40% to 16.56%. (4) Sand accumulation near the plant varies with wind speed. At lower wind speeds, sand deposition concentrates mainly near the front of the plant and between plants, while sand accumulation shifts backward as wind speed increases.

Keywords: sand-fixing service; flow field distribution; numerical simulation; *Alhagi camelorum*; vortex

1. Introduction

Influenced by arid and semi-arid climates, wind-sand flow constitutes the primary form of near-surface material movement in desert regions of western China [?]. Uncontrolled, this can easily lead to ecological degradation in arid and semi-arid areas, causing wind-sand disasters [?]. In these disasters, ground sand particles form the material basis, while wind provides both the shaping force for landforms and the direct dynamic source for wind-sand disasters [?]. Vegetation affects surface soil wind erosion and wind-sand flow structure through multiple advantages including surface coverage, wind decomposition, and sand transport blocking [?]. As a long-term measure for desertification improvement, plant sand fixation technology occupies a dominant position in wind-sand prevention techniques.

Current research on plant wind-sand prevention benefits primarily employs three methods: traditional field observation, simulation experiments (including wind tunnel simulation and numerical simulation), and remote sensing/GIS-based studies. Numerical simulation technology can significantly reduce experimental workload while obtaining data difficult to acquire through field tests. With continuous development in recent years, it has been widely applied in fluid mechanics, wind-sand physics, and wind-sand environments. Numerical simulation studies of plant wind-sand prevention mainly use two models: porous media models, primarily applied to forest and shelterbelt flow fields [?], and direct geometric modeling with physical openings, mostly used for individual plants [?] and plant sand barriers (straw curtain barriers, checkerboard barriers, reed barriers, etc.) [?]. For example, Lai [?] simulated the flow field structure characteristics around single *Populus euphratica* trees, while Chen et al. [?] established simplified models based on reed (*Phragmites australis*) morphological characteristics to analyze wind speed variations and sand accumulation distribution around reed sand barriers, obtaining reasonable layout parameters.

Alhagi camelorum is a typical desert plant with developed root systems and tenacious vitality, representing one of the most common wind-sand prevention plants in western desert regions of China. *Alhagi camelorum* exists as individual plants or shrubs, with size variations across different regions. Larger shrub clusters can cause substantial sand particle deposition and accumulation, forming shrub coppice dunes through long-term wind-sand activity. May to September represents the growth season for *Alhagi camelorum*, during which new shoots emerge from the base of old branches that died the previous year, increasing branch density, height, and crown width, correspondingly increasing regional vegetation coverage. After October, the lignification process causes above-ground parts to dry out in winter. Except for small broken branches at the tips that fall off, most branches remain upright. These standing dry plants can consume wind momentum and reduce shear force. Although living *Alhagi camelorum* plants are very limited in spring, dry standing plants can still produce good wind-sand prevention effects [?]. According to field investigations, the average height of dry *Alhagi camelorum* in the study area during spring is approximately 30 cm, with scattered distribution patterns. Research indicates that sand particle transport in wind-sand movement mainly concentrates within 30 cm of the near-surface layer [**?**].

This study conducts numerical simulation to investigate the influence of spring dry *Alhagi camelorum* on near-surface wind-sand activity in typical desert zones, analyzing flow field variations near plants and validating simulation results through field tests to provide a basis for wind-sand prevention using *Alhagi camelorum* and plant measures in general.

1.1 Study Area Overview Field experiments were conducted at the experimental observation site of the Cele Desert Research Station, Chinese Academy of Sciences. The Cele Station is located in Cele County on the southern edge of the Tarim Basin, at the northern foot of the Kunlun Mountains and the southern margin of the Taklimakan Desert (35°18 -39°30 N, 80°03 -82°10 E). The climate is characterized as an extremely arid continental desert climate, with dryness, large diurnal temperature variations, and long sunshine hours. Water resources are scarce, with an average annual precipitation of 35.1 mm and annual potential evaporation of 2595 mm. Water supply primarily comes from snowmelt in the Kunlun Mountains. The average annual temperature is 11.9 °C, with extreme high temperatures of 41.9 °C and extreme low temperatures of -23.9 °C. The ecosystem is fragile, with desert and Gobi areas covering 2090 km^2. Vegetation consists mainly of perennial desert plants distributed in patches, including mixed communities of *Alhagi camelorum*, *Karelinia caspia*, and *Tamarix chinensis*, with total coverage less than 30% [**?**]. As Cele lies in the downwind region of the two dominant wind directions (NW, NNW) in the Tarim Basin, northwest winds prevail year-round, with frequent wind-sand activity and numerous dust days. The average annual wind speed is 1.9 $\mathrm{m \cdot s^{-1}}$, with 14 days of strong winds above level 8, 240 days of sand-driving winds, and light soil texture prone to wind-sand flow formation. Dust storm weather occurs frequently, with up to 86 days of dust storms and 209 days of blowing sand and floating dust. Spring temperatures rise rapidly with frequent cold air activity, making this period particularly intense for wind-sand activity [**?**].

1.2 Numerical Simulation

1.2.1 Geometric Modeling and Meshing Based on previous modeling studies of vegetation and plant sand barriers [**?**], this study attempts to establish a simplified model of *Alhagi camelorum* in its spring dry state. Due to the difficulty in setting parameters for porous media models, this study adopts a physical opening approach, directly establishing a pore geometry model. Wind-sand flow is a three-dimensional movement phenomenon of sand particles under multiple forces. Since sand particles are primarily affected by gravity and drag forces that basically act in the same plane, a two-dimensional simplified model is established. Considering field experiments and research content, reasonable trial calculations were performed, with the computational domain length set at

30 m and height at 2.7 m to meet flow field development requirements. The plant model height was set at 0.3 m, simplified according to morphology. After multiple modeling simulations and comparing computational load with results, the plant model was finalized. Two plants were placed 7.8 m from the inlet, and the flow field model diagram is shown in [Figure 1: see original paper].

The computational domain mesh type adopts quadrilateral grids, with structured grid division. Since wind-sand flow is significantly affected by the boundary layer and sand particles concentrate near the surface, local grid refinement was applied near the ground and around plants. Five boundary layer grids were divided near the ground surface, and three boundary layer grids on both sides of the plants, with the first layer grid size set at 0.015 mm and increasing at a ratio of 1.2. The computational domain contains a total of 67,200 grids, with minimum orthogonal quality (Minimum Orthogonal Quality) far greater than 0.7 and maximum orthogonal skewness (Maximum Ortho Skew) far less than 0.8, indicating good grid quality that meets computational requirements ([Figure 2: see original paper]).

1.2.2 Boundary Conditions and Computational Parameters According to aerodynamic principles, flow is incompressible when the Mach number is less than 0.3. Wind-sand flow is therefore treated as incompressible flow. The left boundary of the computational domain uses a velocity inlet boundary condition (Velocity Inlet), with wind speed calculated according to formula (1). Since flow velocity and pressure at the outlet are unknown and the flow is fully developed, the right boundary uses a fully developed free outlet condition (Outflow). The upper wall boundary adopts a symmetry condition (Symmetry) to accelerate computation while maintaining accuracy. Plant models and the ground (lower wall) boundary use solid no-slip walls (Wall) with roughness set at 0.002 m.

Sand particles in the medium are considered dilute phase, with wind-sand flow particle sizes generally ranging from 0.075–0.25 mm. Sand particles are approximated as uniform spherical models with particle diameter d = 0.1 mm. Sand density = 2650 $\mathrm{kg \cdot m^{-3}}$, air density = 1.225 $\mathrm{kg \cdot m^{-3}}$, air kinematic viscosity = 1.7894$×10^{-5}$ Pa · s, sand viscosity = 0.047 Pa · s, initial sand particle volume fraction = 0.02%, pressure at standard atmospheric pressure, and gravitational acceleration g = 9.8 $\mathrm{m \cdot s^{-2}}$. The inlet boundary velocity follows a typical wind speed profile flow:

$$v(y) = (u^*/\ ) \cdot \ln(y/y_0)$$

where u* is friction velocity, y_0 is roughness length, is the von Kármán constant (0.41), y is height, and v(y) is wind speed at height y.

The Eulerian two-fluid model is used with an additional turbulence model. The gas-solid phase interaction resistance is calculated using the Schiller-Naumann model. Since temporal variation of the flow field needs to be observed, an unsteady transient solution method is employed, with second-order upwind spatial discretization scheme, time step of 0.001 s, and SIMPLE algorithm for flow field solution.

1.2.3 Control Equations Since heat exchange between wind-sand flows can be neglected, energy equations are not involved. This simulation treats airflow as incompressible flow, with control equations 主要包括 including continuity equation, momentum equation, and turbulence model equations. The standard k- model offers high stability, economy, and computational accuracy with wide applicability, suitable for high Reynolds number turbulence and meeting this study's requirements. This model requires solving turbulence kinetic energy and dissipation rate equations. The turbulence kinetic energy transport equation is derived from exact equations, while the dissipation rate equation is obtained through reasoning and mathematically analogous prototype equations. The turbulence kinetic energy k and dissipation energy equations are as follows:

Turbulence kinetic energy k equation: (k)/ t + (ku)/ x = / x [(+ $/\sigma$) k/ x] + G + G -

Dissipation rate equation: ( )/ t + (u)/ x = / x [(+ $/\sigma$) / x] + C_1 (/k)(G + C_3 G) - C_2 (^{2}/k)

where turbulence viscosity = C k^2/ , C = 0.09 is an empirical constant, G represents turbulence kinetic energy due to mean velocity gradients, G represents turbulence kinetic energy due to buoyancy, t is time, and x , x represent x, y directions respectively. Model constants are: C_1 = 1.44, C_2 = 1.92, σ = 1.0, σ = 1.3.

1.2.4 Wind Protection Efficiency Wind protection efficiency reflects the plant' s effect on reducing airflow, calculated as: (x,z) = [1 - v(x,z)/v(z)] × 100%

where x is horizontal distance from the plant, z is height above ground, (x,z) is wind protection efficiency at point (x,z), v(x,z) is wind speed at (x,z) after passing the plant, and v(z) is initial wind speed at height z without the plant.

1.3 Field Experiment Design To validate simulation reliability, field experiments were conducted at the Cele Desert Research Station observation site. Experiments were performed in March–April when temperatures rise and wind-sand activity is frequent. Sample plots were established on sandy land with naturally growing scattered dry *Alhagi camelorum* and on bare sandy land without vegetation. Plot size was 10 m × 10 m, with *Alhagi camelorum* plots centered on the plant ensuring only one plant per plot. Three sand samplers were arranged along the main wind direction at 0.5 m intervals in the middle position between two plants and at the center of bare sand plots ([Figure 3: see original paper] and). The sand sampler inlet dimensions were 1.5 cm × 3 cm, with 16 collection boxes collecting sand particles from 0–48 cm height at 3 cm intervals. The sampler opening faced the observation period wind direction, with its bottom flush with the ground surface. Collection duration was 10 minutes, opening the sampler inlet at the start and closing it after collection. Collected sand was returned to the laboratory for layered weighing using a precision balance.

Sediment transport rate represents the surface' s sand transport capacity under specific wind speeds and sand source conditions [?]. For consistency, this study uses sediment transport rate as the physical quantity describing wind-eroded material mass per unit time and unit area, with units of $g \cdot cm^{-2} \cdot min^{-1}$. Assuming a sand collection box at a certain height collected sand mass m (g) over time period T (min), the sediment transport rate Q is:

$Q = m/(S \cdot T)$

where S is the sand collection box inlet area (0.00045 m^2).

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2. Results and Analysis

2.1 Flow Field Model Validation Research shows that sand particle volume fraction distribution is consistent with sediment transport rate distribution in wind-sand movement [?]. This study uses field experiment sediment transport rate data as reference, comparing it with sand particle volume fraction variation with height obtained through numerical simulation for validation. [Figure 4: see original paper] shows that sediment transport rate and sand particle volume fraction distributions with height are basically consistent, both fluctuating at 24 cm height, showing a pattern of first increasing then decreasing. This phenomenon relates to the plant' s varying wind protection efficiency at different heights, while vortex effects behind the plant may also influence it. In terms of field experiment sediment transport rate, compared with bare sand surface near-surface sediment transport rate, the rate 0.5 m behind *Alhagi camelorum* is significantly reduced below 30 cm height, demonstrating good sand blocking ability. Validation results show good overall consistency, indicating that flow field settings in the numerical simulation are relatively reasonable and reliable for subsequent simulations.

2.2 Flow Field Characteristics Around Dry *Alhagi camelorum* To investigate flow field characteristics under plant influence, a wind speed profile of 6 $m \cdot s^{-1}$ was selected for simulation (all velocities mentioned below refer to horizontal wind speed at 1.5 m height unless otherwise specified). Flow field variation contours are shown in [Figure 6: see original paper]. The plant clearly alters flow field distribution, creating distinct zones: blocked deceleration zone, lifting acceleration zone, turbulent deceleration zone, and recovery zone. Due to plant obstruction, airflow velocity gradually decreases when approaching the plant. At the plant position, airflow converges and is lifted, with wind speed above the plant increasing. Wind speed at 0.5 m height increases from 4.63 $m \cdot s^{-1}$ to 5.01 $m \cdot s^{-1}$ (8.21% increase). Within the protection distance below plant height, no obvious acceleration zone forms above the plant. Between plants and behind them, wind speed decreases over a considerable distance, forming a large-scale turbulent deceleration zone where sand particles receive reduced kinetic energy and easily deposit. As airflow gradually moves away from the plant area, disturbance weakens and wind speed gradually recovers.

Airflow is compressed at the plant, separates after passing over it, and expands with increased flow cross-section. Due to energy differences, a downward-moving 分流 flow forms, with near-ground airflow returning toward the inlet direction, creating backflow—i.e., reverse airflow in the leeward deceleration zone behind the plant, forming a vortex phenomenon. However, due to the plant' s good porosity, this phenomenon is not particularly pronounced. [Figure 7: see original paper] shows that two main vortex regions form in the flow field: Vortex 1 is located between the two plants, and Vortex 2 is behind Plant 2. Both vortex ranges are relatively large while intensities are weak. The cause may be that after being affected by Vortex 1, airflow is compressed again to form a weak vortex, after which airflow gradually recovers. In vortex regions, sand particles divide into two parts: some follow the recirculating airflow and gradually deposit, while others leave with the vortex airflow into the mainstream flow zone. Larger recirculation zones with weaker intensity result in more sand particles depositing near the plant, indicating stronger sand blocking ability. This reflects that plants are far superior to non-porous obstacles in wind-sand prevention.

2.3 Velocity Distribution and Wind Protection Efficiency

2.3.1 Velocity Distribution Characteristics With 6 $\mathrm{m \cdot s^{-1}}$ as inlet wind speed and wind direction as positive, horizontal velocity components at 0.1 m, 0.2 m, 0.3 m, 0.4 m, and 0.5 m heights were extracted to plot distribution diagrams along the flow path. Except at plant locations where wind speed values are 0, airflow at 1.5 m height remains stable, while airflow at the other four heights experiences varying degrees of disturbance. Horizontal wind speed at 0.4 m and 0.5 m heights first decreases slightly before the plant, increases after being lifted by the plant, then decreases smoothly after passing the plant, finally gradually recovering to initial wind speed at 7.8 m from the inlet. Overall, except at plant locations, horizontal wind speed variation along the path is relatively gentle without severe disturbance, remaining below inlet wind speed over a large range, which helps suppress wind-sand flow and promote sand particle deposition.

At 0.1 m, 0.2 m, and 0.3 m heights, horizontal wind speed shows a "decrease-increase-decrease" pattern after passing the plant. Between the two plants, wind speed operation is relatively stable. Horizontal wind speed at 0.4 m height increases by a maximum of 7.87% along the path, while at 0.5 m height it can be reduced by a maximum of 39.93%. The increase amplitudes are similar, while decrease amplitudes show a pattern of being larger closer to the ground.

With 6 $\mathrm{m \cdot s^{-1}}$ as inlet wind speed, vertical cross-sections were taken at 4.5 m, 5.6 m, 7.2 m, and 7.8 m from the inlet to plot horizontal wind speed component distributions with height. [Figure 9: see original paper] shows that at 4.5 m (between plants), horizontal wind speed increases relatively steadily with height, as this position is less affected by the plant. At 5.6 m and 7.2 m (behind plants), horizontal wind speed below 0.6 m shows a "decrease-increase-decrease" distribution. As height continuously increases, horizontal wind speed decreases to negative values (backflow), primarily existing within 0.1–0.3 m height, with minima at 0.12–0.14 m. Negative values of -0.23 $\mathrm{m \cdot s^{-1}}$, -0.15 $\mathrm{m \cdot s^{-1}}$, and -0.08 $\mathrm{m \cdot s^{-1}}$ appear at 5.6 m and 7.2 m at heights of 0.1 m, 0.2 m, and 0.3 m respectively. As height increases, horizontal wind speed at 7.8 m shows an overall pattern of increasing with height, with 0.1 m height as the node: backflow below and forward flow above. This confirms the earlier analysis of large recirculation zones. Overall, 0.6 m height is an important demarcation point for wind speed development: wind speed is first reduced below this height, then develops with greater acceleration within 0.3–0.6 m, and is almost unaffected by the plant above it, recovering to logarithmic distribution.

2.3.2 Plant Wind Protection Efficiency During wind-sand flow movement, sand particles mainly concentrate within 0.3 m of the near-surface layer. Therefore, wind protection efficiency at 0.1 m, 0.2 m, and 0.3 m heights was studied at wind speeds of 6 $\mathrm{m \cdot s^{-1}}$, 10 $\mathrm{m \cdot s^{-1}}$, and 20 $\mathrm{m \cdot s^{-1}}$. [Figure 10: see original paper] shows that wind protection efficiency generally decreases with distance from the plant. When inlet wind speed is 6 $\mathrm{m \cdot s^{-1}}$, wind protection efficiency within 5.3 m behind the plant exceeds 16.56% at all heights, with wind speeds at various heights approaching each other at 7.4 m. Wind protection efficiency at 0.1 m height decreases to 5.3% at 4.26 m, then decreases rapidly after 5.3 m. At 0.2 m and 0.3 m heights, wind protection efficiency shows more stable decreasing trends with distance from the plant, with efficiency at 0.3 m height decreasing to 16.56% at 5.3 m.

Overall, wind protection efficiency decreases with increasing wind speed, a phenomenon that becomes more obvious with height. At lower wind speeds, plants have larger protection ranges and higher wind protection efficiency. At higher wind speeds, wind protection efficiency is higher near the ground, but after reaching a certain distance, its decreasing rate increases and plants quickly lose effective protection, with protection range correspondingly reduced.

2.4 Sand Accumulation Characteristics Around Dry *Alhagi camelorum* Wind is the direct driving force for sand particle movement, and changes in wind speed directly affect sand particle motion status. Influenced by plants, on one hand reduced wind speed causes sand particle deposition; on the other hand, moving sand particles are blocked by plants, forming sand accumulation. To investigate plant effects on sand accumulation under different wind speed conditions, inlet wind speeds of 6 $\mathrm{m \cdot s^{-1}}$, 10 $\mathrm{m \cdot s^{-1}}$, and 20 $\mathrm{m \cdot s^{-1}}$ were simulated to obtain sand accumulation contours around plants ([Figure 11: see original paper]).

Under different wind speed conditions, sand accumulation increases over time and reaches a stable state at a certain moment (t = 10 s). At 6 $m \cdot s^{-1}$ inlet wind speed, sand particles first deposit near Plant 1 and on the windward side of Plant 2, then continuously accumulate at Plant 2 and between the two plants. Sand accumulation near Plant 2 is significantly greater than near Plant 1, caused by airflow obstruction and wind speed reduction decreasing sand transport capacity, corresponding to earlier wind speed analysis results. At 10 $m \cdot s^{-1}$ inlet wind speed, sand accumulation also forms near Plant 2 and between plants, but sand accumulation near Plant 1 decreases compared with the 6 $m \cdot s^{-1}$ case at the same time, with more sand accumulation appearing behind Plant 2. As inlet wind speed increases to 20 $m \cdot s^{-1}$, sand accumulation near Plant 1 shows little difference between t = 5 s and t = 10 s, with only small amounts of accumulation, while large amounts of sand accumulate before and after Plant 2, even forming small dunes.

Analysis reveals that wind-sand flow velocity changes significantly when passing plants. At lower wind speeds, Plant 1' s reduction effect decreases flow velocity below the sand-driving wind speed within a certain range before and after it, putting wind-sand flow in a supersaturated state and causing sand particle deposition and accumulation. At higher wind speeds, although Plant 1 reduces wind speed, its reduction capacity is limited and wind speed remains above the sand-driving wind speed, keeping wind-sand flow in an unsaturated state where only small portions of sand particles deposit due to obstruction while most continue moving. Plant 2 then provides secondary reduction, greatly decreasing nearby wind speed and causing large amounts of sand deposition. Meanwhile, recirculation behind Plant 2 also promotes sand deposition.

The study demonstrates that plants have good sand blocking ability. Under different wind speed conditions, sand accumulation increases over time and stabilizes. At lower wind speeds, sand accumulation concentrates mainly near the front of plants and between plants. As wind speed increases, sand particles deposit after multiple reductions by airflow, showing a backward shifting trend in sand accumulation. Over time, as wind-sand flows of different velocities alternate, sand particles continuously accumulate near plants, which also adapt to wind-sand activity through physiological processes. Through long-term interaction, sand dunes form near plants—the commonly called shrub coppice dunes. These dunes vary in size from tens of centimeters to several meters, depending on plant size, wind-sand activity intensity, local environmental characteristics, and other factors. Since field wind speeds are variable, plants in front can cause sand deposition at lower wind speeds, but higher wind speeds require 叠加 superposition effects from plants behind. Therefore, multiple plants more easily form shrub coppice dunes than single plants, and their formation is also affected by plant layout. When using plants or plant-like materials for wind-sand prevention, regional wind speed characteristics should be considered. In areas prone to high wind speeds, double or multiple rows should be arranged to achieve better effects.

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3. Discussion

Many factors cause wind-sand disasters and affect soil wind erosion intensity, including wind fields, soil properties, and surface conditions, with vegetation coverage being one of the main influencing factors of surface conditions. Since regional wind fields and soil properties are relatively fixed, using vegetation to alter surface conditions for wind-sand prevention and erosion control is a highly effective measure, making research on flow field characteristics under vegetation influence particularly critical. However, due to the extreme complexity of vegetation and its influenced surfaces, vegetation with different coverage, height, canopy porosity, and configuration patterns differentially affects surface material conditions and wind speed [?], making this research challenging.

Vegetation primarily affects wind-sand activity through two mechanisms. First, plants alter flow field characteristics, reduce wind speed, and obstruct sand particles, causing deposition. Xu et al. [?] studied the sand fixation effects of *Haloxylon ammodendron* forests under three configuration patterns through wind tunnel experiments, showing that different patterns affect flow field operation characteristics and change sand fixation effects, though differences become insignificant when vegetation coverage exceeds 32.37%. For small shrubs, plant morphology influences results—plants with large under-branch heights create "venturi effects" that accelerate surface wind erosion, while low-stature plants with small porosity show more obvious wind-sand prevention effects and larger effective protection distances [?]. Second, plants form organic layers through biological processes, fixing soil, reducing surface shear force, increasing surface sand-driving wind speed, and decreasing sand particle movement amplitude to achieve wind-sand prevention. Wang et al. [?] studied soil erodibility factors under different plant communities in the Ulan Buh Desert, finding that shrub communities like *Haloxylon ammodendron* and *Nitraria tangutorum* reduce soil wind erosion more than herbaceous communities like *Agriophyllum squarrosum* and *Kalidium foliatum*. Wu et al. [?] demonstrated that plants promote soil crust formation and development, giving soil stronger water storage capacity and wind erosion resistance. Numerical simulation methods can effectively reflect the protective effects of the first wind-sand prevention mechanism but struggle to comprehensively reflect plants' biological effects.

During different phenological periods, plants show differences in canopy morphology, branch flexibility, leaf area, and resulting above-ground biomass allocation patterns, leading to varying sand blocking capacities [?]. Shrub dune height is controlled by plant height, dune radius by crown width, and dune growth and development are affected by morphological parameters [?]. Based on differences between growing season and non-growing season *Alhagi camelorum* in height, crown width, and porosity [?], this study' s plant model uses smaller height and crown width with larger porosity to represent non-growing season *Alhagi camelorum* morphology, providing certain reliability. Future research should optimize growing season plant models while considering plant biological effects and field non-steady inflow factors to obtain more comprehensive and accurate results.

Meanwhile, simulation results reveal flow field operation at the extremely small scale of two plants, while large-scale background flow fields under different vegetation coverage represent another important research content [?]. Small-scale and large-scale environments are closely related—small-scale environments affect large-scale flow field operation, while large-scale environments can further reflect small-scale conditions. Therefore, establishing mutual verification between the two is crucial.

4. Conclusions

This study simplifies the morphology of 30 cm tall dry *Alhagi camelorum* to establish a two-dimensional model, uses numerical simulation to investigate wind speed and sand accumulation characteristics after wind-sand flow passes the plants, and validates reliability through field experiments. The main conclusions are:

1. The flow field near plants can be roughly divided into blocked deceleration zone, lifting acceleration zone, turbulent deceleration zone, and recovery zone. Two weak vortices form around plants, located between the two plants and behind Plant 2, with recirculation zones mainly existing within 1.2–2.7 m. The recirculation height near plants is 0.09–0.14 m, while recirculation height farther from plants is below 0.1 m.
2. At 6 $\mathrm{m \cdot s^{-1}}$ wind speed, 30 cm plants mainly affect horizontal wind speed below 0.6 m height. After leaving the area between the two plants, wind speed gradually recovers to its initial state, showing a "decrease-increase-decrease" distribution along the path. Horizontal wind speed at a certain distance behind the plant no longer follows a strict logarithmic distribution with height but shows two minima, rapidly increasing with height in the 0.3–0.6 m range before gradually recovering to the initial wind speed profile.
3. Plant wind protection efficiency generally decreases with increasing wind speed, a phenomenon that becomes more obvious with height. Due to good plant porosity, overall wind protection efficiency is good with large protection distances. At 6 $\mathrm{m \cdot s^{-1}}$ wind speed, wind protection efficiency within 5.3 m behind the plant exceeds 40% below 0.3 m height, decreasing to 16.56% when wind speed increases to 10 $\mathrm{m \cdot s^{-1}}$.
4. Plants demonstrate good sand blocking capacity. Under different wind speed conditions, sand accumulation increases over time and reaches stability. At lower wind speeds, sand accumulation concentrates mainly near the front of plants and between plants. As wind speed increases, sand

particles deposit after multiple reductions by airflow, showing a backward shifting trend in sand accumulation.

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References

[References are preserved as originally formatted in the input]

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