Postprint: Numerical Simulation of Windbreak and Sand Fixation Effects of *Reaumuria songarica*

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Abstract

Phytogenic sand fixation constitutes one of the vital measures for preventing and controlling wind-sand disasters in arid and semi-arid regions of northern China. Reaumuria soongorica, the most widely distributed subshrub in desert areas, holds significant application value. This study utilizes the Fluent computational platform to conduct numerical simulation of the flow field around Reaumuria soongorica plants, analyzing wind speed characteristics and sand accumulation characteristics. The results indicate: (1) Under an initial wind speed of 10 m · s–1, vortices form both in front of and behind the plant, with their height and intensity related to the distance from the plant, overall below 0.25 m. (2) Numerical simulation results demonstrate that variations in horizontal airflow velocity predominantly exhibit "N" and "W" shaped curves, while vertical airflow velocity variations exhibit "V" shaped curves. (3) At lower wind speeds, the windbreak efficiency of non-growing season Reaumuria soongorica surpasses that of growing season plants, with a protective distance of 4 m behind the plant; when wind speed exceeds 6 m · s–1, the wind speed reduction behind double-row growing season Reaumuria soongorica can exceed 94.45%. (4) Reaumuria soongorica exhibits excellent sand-blocking effects; at an initial wind speed of 6 m · s–1, most sand particles accumulate at the base in front of and behind the plant; when wind speed increases to 10 m · s–1, growing season Reaumuria soongorica demonstrates effective sand blocking, with sand particles mainly depositing at 1.5–3 H behind the plant, and sand accumulation height less than 0.1 m; at an initial wind speed of 15 m · s–1, sand accumulation behind growing season Reaumuria soongorica is primarily distributed at 2–3.5 H behind the plant, while sand particle accumulation range for non-growing season plants extends from 1–10 H behind the plant. Regardless of growing season, Reaumuria soongorica can effectively reduce airflow velocity within the wind field and exhibits favorable sedimentation effects on sand particles carried by the airflow, playing a significant role in phytogenic sand control engineering.

Numerical Simulation of the Windbreak and Sand-Fixation Effects of *Reaumuria soongorica*

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Abstract

Vegetation-based sand fixation represents a critical measure for controlling wind and sand disasters in the arid and semi-arid regions of northern China. *Reaumuria soongorica*, a semi-shrub widely distributed across desert areas, holds significant practical value for such applications. This study employed the Fluent computational platform to conduct numerical simulations of airflow fields around *R. soongorica* plants, analyzing wind speed characteristics and sand accumulation patterns. The results demonstrate that: (1) At an initial wind speed of 10 $\mathrm{m \cdot s^{-1}}$, vortices form both upstream and downstream of the plant, with their height and intensity varying with distance from the plant, generally remaining below 0.25 m. (2) Numerical simulation results indicate that changes in horizontal airflow velocity predominantly exhibit N-shaped and W-shaped curves, while vertical airflow velocity changes follow a V-shaped pattern. (3) At lower wind speeds, the wind-blocking effectiveness of *R. soongorica* during the non-growing season surpasses that during the growing season, with a protection distance of 4 m behind the plant; when wind speeds exceed 6 $\mathrm{m \cdot s^{-1}}$, the wind speed reduction behind double rows of growing-season *R. soongorica* can exceed 94.45%. (4) *R. soongorica* demonstrates excellent sand-blocking effects. At an initial wind speed of 6 $\mathrm{m \cdot s^{-1}}$, most sand particles accumulate at the base of the plant, both in front of and behind it. When wind speed increases to 10 $\mathrm{m \cdot s^{-1}}$, growing-season *R. soongorica* effectively blocks sand, with particles primarily depositing 1.5–3 H behind the plant at heights below 0.1 m. At an initial wind speed of 15 $\mathrm{m \cdot s^{-1}}$, sand deposition behind growing-season *R. soongorica* mainly distributes between 2–3.5 H, whereas sand accumulation behind non-growing-season plants ranges from 1–10 H. Regardless of growth season, *R. soongorica* effectively reduces airflow velocity within the wind field and promotes settlement of sand particles carried by the airflow, playing a vital role in vegetation-based sand control projects.

Keywords: windbreak and sand fixation; *Reaumuria soongorica*; wind speed variation; sand deposition distribution; Fluent

Introduction

Sandy desertification constitutes one of the most pressing ecological crises of international concern. Given China's vast territory and diverse topography, desertification poses particularly severe challenges, especially in the northwestern region where harsh natural conditions and extensive deserts and gobi landscapes prevail. Consequently, domestic scholars have conducted extensive research on wind-sand movement patterns and their hazards, proposing corresponding mitigation measures. The implementation of the "Belt and Road" initiative has further elevated desertification prevention and control in northwestern arid and semi-arid regions as an urgent environmental priority.

Vegetation protects the land surface, and phytogenic sand fixation has emerged as a primary long-term strategy for desertification amelioration. The principle involves using low shrubs to block wind and sand, substantially reducing surface wind speeds to promote sand particle settlement and thereby decreasing soil wind erosion. Researchers worldwide have investigated vegetation's windbreak and sand-fixation benefits through field observations, wind tunnel experiments, and numerical simulations. For instance, Niu et al. used wind tunnel experiments to simulate *Haloxylon ammodendron* under different planting configurations, concluding that a "small spacing, large row distance" triangular arrangement offered superior wind protection. Cheng et al. examined three herbaceous plant morphotypes through wind tunnel testing, determining wind erosion inhibition rates and finding that high vegetation cover significantly suppresses erosion. Numerical simulation technology, valued for its convenience, reliability, and cost-effectiveness, has been widely applied in heat transfer, mechanical design, fluid mechanics, and other fields. Lai conducted numerical simulations of flow field structures around individual *Populus euphratica* trees, while Bo and Zheng performed numerical simulations of sand barriers, determining effective protection distances and analyzing influencing variables. Chen et al. investigated optimal spacing for multi-row sand barriers through numerical simulation of high-standing reed barriers.

Reaumuria soongorica, a salt-tolerant semi-shrub, primarily inhabits alluvial and proluvial plains and eroded gobi surfaces in desert regions. As a dominant and constructive species widely distributed across China's desert areas, it represents a common clustered dwarf shrub vegetation. Through long-term adaptation to harsh environments, *R. soongorica* has developed unique architectural characteristics, with its branch system effectively blocking wind-blown sand and promoting deposition. The species has also been applied in shelterbelt construction within the Three-North Shelter Forest Program. This study employs numerical simulation to investigate *R. soongorica* as a research subject, analyzing wind speed changes, sand deposition distribution, and flow field characteristics to evaluate its windbreak and sand-blocking benefits in desert grasslands. Validation against existing wind tunnel experiments provides support for applications of *R. soongorica* and other plant measures in windbreak and sand-fixation projects.

1.1 Study Object

The study area is located in Cele County, Hotan Prefecture, Xinjiang, characterized by a fragile ecosystem where natural vegetation consists primarily of perennial desert plants including *Alhagi camelorum*, *R. soongorica*, and *Allium polyrhizum*. Previous numerical simulations of vegetation have typically simplified plant models to two-dimensional representations. Although these simplifications are similar, model parameters vary according to plant type. This study selected *R. soongorica* as the research subject. While *R. soongorica* occurs in communities in the field, large continuous stands are rare. Numerical simulation of two plants provides more effective guidance for designing sparse shrub belts. Based on existing field investigations, surveys were conducted during both growing and non-growing seasons within 25 m × 25 m sample plots in *R. soongorica* communities. Same-age plants were regularly monitored to record crown width, branch length, and plant density per meter, with average values calculated as modeling references (Table 1).

[Figure 1: see original paper] Plant model of *R. soongorica* in growing season and non-growing season
R. soongorica survey statistics table
[Figure 2: see original paper] Simplified diagram of watershed model

1.2.1 Geometric Modeling and Boundary Condition Settings

This simulation primarily focused on wind and sand particles. In wind-sand movement, sand particles are primarily subject to vertically downward gravity and horizontal drag forces—two perpendicular forces acting within the same plane—allowing simplification of the watershed model to two-dimensional calculations. Drawing software was used to create 2D models, which were then imported. The computational domain measured 25 m × 2 m, with plants positioned 5 m and 12.5 m from the inlet, as shown in the geometric model. Meshing was performed using Ansys Icem CFD with a hybrid meshing approach. The model region was determined to be 25 m long through multiple trial calculations and simulations. The mesh consisted of approximately 1.1×10^5 structured grid cells with excellent quality, meeting computational requirements.

1.2.2 Parameter Settings

Based on existing research results, airflow was treated as incompressible flow. Roughness height was set at 0.001 m with default roughness length. Sand particle diameter was set at $d = 0.1$ mm, density $= 2650\ \mathrm{kg \cdot m^{-3}}$, initial sand volume fraction $\alpha = 0.625$, and viscosity $= 0.047\ \mathrm{Pa \cdot s}$. A wind speed profile equation was loaded at the inlet:

Boundary conditions were configured as follows:
(1) Inlet boundary: The air phase inlet velocity was defined by the wind speed profile equation (Equation 1), with a velocity inlet selected and the profile loaded via compiled UDF for greater applicability and reliability in reproducing real wind speed variations. The compiled UDF is converted to machine code upon loading into Fluent, substantially improving computational efficiency and reducing costs.

(2) Outlet boundary: A free outlet was adopted to allow free outflow of wind and sand, better approximating actual conditions.
(3) Upper and lower wall boundaries: The lower wall was set as a fixed no-slip boundary, while the upper wall was set as a symmetric boundary.

This numerical simulation employed the Eulerian two-fluid model with the Phase Coupled SIMPLEC algorithm, which is suitable for incompressible flow and accelerates iterative convergence.

1.2.3 Control Equations

The computation primarily utilized continuity equations, momentum equations, and the k- turbulence model equations. The turbulent kinetic energy k and dissipation rate equations are as follows:

where is the turbulent viscosity coefficient; G and G represent generation terms for turbulent kinetic energy; is the turbulent dissipation rate; $\sigma = 1.3$ and $\sigma = 1.0$ are model constants; C_1 and C_2 are empirical constants; x represents coordinate components; and u represents velocity components.

Results

2.1.1 Net Wind Field Speed Simulation Validation

Numerical simulation technology has been widely applied across various fields due to its convenience, reliability, and low cost. Given experimental limitations, this study validated simulation feasibility against existing wind tunnel test data. Both simulated and measured wind speeds increased with height above ground, with wind tunnel speeds slightly higher than simulated values but showing close agreement. This confirms the feasibility and reliability of the current simulation.

2.1.2 Wind-Sand Two-Phase Flow Validation

This study selected wind tunnel experiments by Wang Lu for numerical simulation validation. Experimental plants were collected from the Ulan Buh Desert. Wind tunnel tests were conducted at the Desert Forestry Experimental Center of the Forestry Science Research Institute in Dengkou County, Inner Mongolia, with a computational domain of 25 m × 2 m × 0.05 m. A sand bed 0.05 m high was laid in the wind tunnel center at a wind speed of $10\ \mathrm{m \cdot s^{-1}}$. Six different plant morphologies were placed in the test section center, with wind speeds measured using Pitot tubes and sand accumulation measured with sand collectors. Sand volume fraction changes behind *Calligonum mongolicum* and *R. soongorica* were compared with simulation results (Figure 5). The simulation results align well with Wang Lu's wind tunnel data, showing minimal variation in sand volume fraction above 0.02 m height and dramatic changes below 0.02 m, with basic agreement between simulation and experiment.

2.2 Flow Field Characteristics Around *R. soongorica*

Under the influence of double-row *R. soongorica*, the simulation domain formed four distinct zones: deceleration zone, acceleration zone, recirculation zone, and recovery zone (color depth corresponds to wind speed, with blue indicating minimum speed). The growing-season *R. soongorica* showed clear stratification of horizontal airflow velocity at the inlet. Comparing horizontal wind speed contours between non-growing and growing seasons reveals that non-growing season contours were relatively sparse from inlet to first plant row, with stable wind speed increase with height. In contrast, growing-season contours were dense below plant height (0.34 m), with dramatic wind speed variations. As the flow field developed, near-surface airflow encountered the first plant row. Due to the blocking effect of *R. soongorica*, airflow was compressed and lifted, with slight velocity increase on the windward side. Wind speed changed dramatically above the first plant row, increasing rapidly. Although airflow above growing-season plants varied intensely, the increase amplitude was smaller, indicating more significant wind speed reduction. Due to blocking by the first row, wind speed recovery behind the plants was slow; encountering the second row caused another velocity decrease, forming a recirculation zone with low airflow velocity where sand particles readily deposited. After being lifted by the second row, wind speed increased slowly above the plants, then decreased, forming another recirculation zone behind the second row. At 0.5–1 m behind the second row, airflow speed began recovering due to distance from the plants. After two blocking actions by the plants, airflow kinetic energy decreased substantially, causing large sand deposits at the first row, between rows, and behind the second row.

2.3 Airflow Velocity Distribution Characteristics Around *R. soongorica*

Since airflow velocity decreases significantly after passing plants, facilitating sand particle settlement, plant-based sand control has become the mainstream approach. This simulation defined the inlet direction as positive and extracted horizontal velocities at heights of 0.1 m, 0.2 m, 0.3 m, 0.4 m, and 0.5 m to plot along-path distributions (Figure 7). All five heights experienced varying degrees of disturbance, with overall horizontal velocity curves showing “M” shapes. As airflow entered the field, speed gradually increased. After encountering the first plant row, wind speed decreased significantly, dropping to $2.91\ \mathrm{m \cdot s^{-1}}$ and $2.69\ \mathrm{m \cdot s^{-1}}$ at heights of 0.1 m and 0.2 m respectively (from an initial $6.5\ \mathrm{m \cdot s^{-1}}$), then rebounded slightly between rows to $3.93\ \mathrm{m \cdot s^{-1}}$ and $2.16\ \mathrm{m \cdot s^{-1}}$. After the second row, wind speed decreased again to $2.52\ \mathrm{m \cdot s^{-1}}$ and $2.17\ \mathrm{m \cdot s^{-1}}$, then increased rapidly and stabilized. At 0.3 m, 0.4 m, and 0.5 m heights, velocities decreased then increased, then decreased again, all remaining below initial wind speed. At 0.5 m height, velocity decreased slightly, increased after plant lifting, then remained stable with minor reduction after passing the plants.

Vertical velocity profiles were extracted at three cross-sections: between plants, behind the first row, and behind the second row (Figure 8). In the non-growing season flow field, airflow fully developed after passing the plants, eventually restoring logarithmic distribution. In the growing-season field, post-plant airflow converged to similar values after full development, indicating slower recovery and greater wind speed reduction behind growing-season plants, thus providing better wind protection.

In the growing-season *R. soongorica* flow field, wind speed variation below plant height (0.34 m) followed consistent patterns with the non-growing season. At 0.5 m height, the velocity curve showed a "W" shape, indicating that after passing the double rows, wind-blown sand flow maintained a decreasing trend. At different heights, wind speed variation curves eventually converged after temporal development. The vertical cross-section between plants showed rapid velocity increase below 0.3 m, with non-growing season speeds increasing from 1.32 $\text{m} \cdot \text{s}^{-1}$ to 2.32 $\text{m} \cdot \text{s}^{-1}$ at 0.1–0.3 m, then slowly increasing above 0.3 m to restore logarithmic distribution. Growing-season velocities increased slowly above 0.3 m, reaching maximum speeds of 7.1 $\text{m} \cdot \text{s}^{-1}$ with large variation amplitudes but decreasing gradually above 0.6 m. In summary, airflow velocity first increased then decreased with height, with the inflection point at 0.3–0.6 m. Below 0.3 m, velocity changed rapidly with large amplitude; above 0.6 m, airflow was essentially unaffected by plants and restored to logarithmic distribution. Therefore, the plant protection height is 0.6 m, though the issue of significant wind speed increase above this height requires attention.

Wind provides energy for sand particle movement, making wind speed the key factor affecting sand transport. When airflow passes plants, velocity decreases and the kinetic energy of wind-blown sand diminishes, causing sand deposition. Additionally, sand particles tend to accumulate when blocked by plants. To investigate the relationship between sand deposition and wind speed development over time, this study simulated sand accumulation behind both growth-season types and compared accumulation cloud maps at time T = 20 s (Figures 9 and 10). Over time, airflow velocity gradually decreased and sand deposition increased, eventually stabilizing. In both growth-season flow fields, early-stage sand accumulation patterns were basically consistent. At T = 20 s, sand entered the flow field, forming minor deposits from inlet to 5 m downstream and accumulating before the first plant row. Due to significant airflow reduction by the first row, wind-blown sand energy was redistributed, converting kinetic energy to gravitational potential energy, resulting in much smaller sand accumulation before the second row compared to the first row. At T = 20 s, large sand deposits appeared behind the second row in both seasons. Non-growing season sand primarily deposited at 1–3.5 m behind plants with accumulation heights of 0.05–0.12 m, while growing-season sand accumulated mainly between plants and around the second row at heights of 0.05–0.1 m.

High wind residual coefficient under two wind speeds

Discussion

Extensive research has accumulated on the causes of wind-sand disasters and factors affecting soil erodibility, with scholars focusing primarily on wind fields, surface conditions, and vegetation cover. Since various factors affecting wind erosion remain stable without external forces, increasing vegetation coverage enhances soil resistance to wind erosion, and plant architecture effectively mitigates wind-sand disasters, making phytogenic sand control one of the most effective measures. This study's Fluent numerical simulation of double-row *R. soongorica* significantly altered wind-blown sand flow field distribution, creating deceleration, acceleration, recirculation, and recovery zones. Influenced by *R. soongorica*'s unique architecture, recirculation zones formed on windward and leeward sides, with vortex intensity affecting sand deposition distribution—consistent with Li et al.'s findings on tree windbreak effects under strong winds. Further analysis revealed that morphological differences between growth seasons produced varying windbreak and sand-blocking effects. Growing-season *R. soongorica*, with denser branches and leaves, significantly increased sand-blocking capacity. Below plant height (1–2 H), wind speed varied dramatically with large sand deposition; between 1.5–3 H, wind speed gradually recovered with reduced deposition. In contrast, non-growing season plants only affected wind speeds below plant height. Zheng et al.'s wind tunnel experiments on *Buxus sinica* under dust storm conditions showed significant sand concentration reduction within the canopy height range (0.2–1 H), consistent with this study's results.

Analysis of wind speed characteristics revealed that non-growing season along-path wind speed curves showed "M" shapes, while growing-season curves below plant height were "W" shaped, transitioning to "M" shape above 1–1.5 H. This difference arises because growing-season plants have higher protection heights, resulting in slower wind speed recovery below 0.6 m and more stable variation—consistent with the above discussion. In summary, growing-season *R. soongorica* provides more significant windbreak effects, with plant structure more effectively regulating wind speed and helping reduce wind speed across a greater height range.

This study's simulation results align well with existing wind tunnel data, validating the reliability of the numerical simulation approach. Current numerical simulations of wind-sand movement primarily focus on tall trees, sand barriers, straw checkerboards, and retaining walls—methods that are time-consuming, labor-intensive, and costly with low ecological-economic benefits. This study selected economically valuable *R. soongorica* as the research subject (Figure 11), which possesses good forage and medicinal value, enabling better integration with local planting conditions.

[Figure 11: see original paper] *R. soongorica* sand-dune shrubland

Conclusions

This study investigated *R. soongorica* using Fluent numerical simulation to compute flow field characteristics and sand deposition distribution after airflow passed the plants, yielding the following conclusions:

1. The flow field around *R. soongorica* divides into deceleration, acceleration, recirculation, and recovery zones, with two vortices existing between plants and behind plant rows. Growing-season wind speed along-path distribution curves show “W” shapes with slow recovery and stable variation, while non-growing season curves show “M” shapes with rapid recovery and dramatic variation behind plants.
2. *R. soongorica* exhibits good porosity and thus effective windbreak performance, with windbreak efficiency decreasing with increasing height. Growing-season plants rapidly reduce wind speed below 0.3 m height, while non-growing season plants show more stable wind speed variation. The protection height for growing-season *R. soongorica* is twice plant height (0.6 m), achieving 94.5% wind speed reduction, while non-growing season protection height is only 0.3 m, above which wind speed restores to logarithmic distribution.
3. Growing-season *R. soongorica* has greater biomass and stronger inter-plant interactions, forming higher sand mounds near plants, while non-growing season plants with reduced biomass show more dispersed sand distribution. Near-plant vortices are low-speed and concentrated below plant height. Growing-season sand accumulates mainly between plants and around the second row at heights of 0.05–0.1 m, while non-growing season sand distributes more widely behind plants at 1–3.5 m.
4. Double-row *R. soongorica* provides excellent sand-blocking effects. In both growth-season flow fields, sand deposition before and after plants continuously increases after full flow field development, eventually stabilizing under current wind speed conditions.

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