Effects of Stand Density and Planting Pattern on the Windbreak Effect of Haloxylon ammodendron Plantations (Postprint)

Authors: Niu Danni, Han Rong, Ma Rui, Wang Zhenting, Liu Hujun, Wei Linyuan, Ma Rui

Date: 2023-03-13T00:00:00+00:00

Abstract

This study investigated the effects of different densities and planting point configurations on the windbreak effectiveness of Haloxylon ammodendron plantations, providing a scientific basis for optimizing the structure of windbreak and sand-fixation forests in arid regions. Using H. ammodendron as a prototype, simulated plants were employed to design three densities and four planting point configurations of belt-shaped forests in a staggered arrangement. The designations and corresponding plant and row spacings were A: 17 cm × 17 cm, B1: 34 cm × 17 cm, B2: 17 cm × 34 cm, and C: 34 cm × 34 cm. Through wind tunnel simulation experiments, the flow field and windbreak effects were measured and analyzed when the forest belt density and planting point positions varied. The results showed that: (1) The areas of wind speed reduction zones ($U/U0 < 1$) for forest belts A, B1, B2, and C accounted for 78.06%, 70.41%, 74.36%, and 82.80% of the total flow field area, respectively; the areas of weak wind zones ($U/U0 < 0.4$) accounted for 22.46%, 0.73%, 5.91%, and 0% of the total flow field area, respectively; (2) The greater the stand density, the smaller the average wind speed under the canopy, but the faster the wind speed recovery in the near-surface layer behind the forest belt. The minimum wind speed points for forest belts A, B1, B2, and C were located at 11H, 15H, 15H, and 20H behind the belt, respectively (where H is tree height); (3) The ranking of windbreak effectiveness for the four forest belts from largest to smallest was A > B2 > B1 > C. The relationship between forest belt windbreak effectiveness and stand density was nonlinear, with the proportional relationship of near-surface wind speed reduction behind the belt being approximately A:B:C 6:3:2. In practical afforestation, planting density should be determined according to soil water carrying capacity, and on this basis, the planting point configuration of “small spacing between plants, large spacing between rows” should be prioritized.

Full Text

Preamble

Effects of Stand Density and Planting Point Configuration on Windbreak Efficiency of Artificial Haloxylon ammodendron Forests

Vol. 40 No. 1 Jan. 2023

Authors: NIU Danni[1], HAN Rong[1], MA Rui[1], WANG Zhenting[2], LIU Hujun[3], WEI Linyuan[3]

Affiliations:
[1]College of Forestry, Gansu Agricultural University, Lanzhou, Gansu, China
[2]Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, Gansu, China
[3]Gansu Desert Control Research Institute, Lanzhou, Gansu, China

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Abstract

This study investigated the effects of different densities and planting point configurations on the windbreak efficiency of Haloxylon ammodendron forests to provide a scientific basis for optimizing windbreak structures in arid regions. Using Haloxylon ammodendron as a prototype, simulation plants were designed with three stand densities and four planting point configurations: A (17 cm × 17 cm), B1 (34 cm × 17 cm), B2 (17 cm × 34 cm), and C (34 cm × 34 cm). Wind tunnel simulation experiments were conducted to measure and analyze the flow field and windbreak efficiency under varying density and planting point conditions. Results demonstrated that: (1) The wind speed deceleration zone ($U/U_0 < 1$) accounted for 78.06%, 70.41%, 74.36%, and 82.80% of the total flow field area for configurations A, B1, B2, and C, respectively. The weak wind zone ($U/U_0 < 0.4$) occupied 22.46%, 0.73%, 5.91%, and 0% of the total flow field area. (2) Higher stand density resulted in lower average wind speed beneath the canopy, but faster wind speed recovery in the near-surface layer behind the windbreak. The minimum wind speed points were located at 11H, 15H, 15H, and 20H behind windbreaks A, B1, B2, and C, respectively (where H is tree height). (3) The windbreak efficiency ranking from highest to lowest was A $>$ B2 $>$ B1 $>$ C. The relationship between windbreak efficiency and stand density was nonlinear, with the near-surface wind speed reduction ratio of A:B:C 6:3:2 behind the windbreaks. In practical afforestation, planting density should be determined based on soil water carrying capacity, with priority given to the "small plant spacing, large row spacing" configuration.

Keywords: windbreak and sand fixation forest; Haloxylon ammodendron; density; planting point configuration; flow field; windbreak efficiency; wind tunnel simulation

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1 Materials and Methods

1.1 Experimental Materials

In wind tunnel experiments, satisfying geometric similarity is particularly crucial for obtaining reliable results. Following established methodologies, we used simulation plant models as experimental materials, with vigorous field-grown Haloxylon ammodendron individuals serving as prototypes. The spatial architecture and porosity of the models were adjusted by modifying branch angles and trimming foliage. The scale ratio between the models and actual Haloxylon ammodendron plants was 1:15. The main stems and branches were constructed from plastic-coated wire, while twigs and leaves were made of plastic to ensure realistic swaying behavior under wind conditions. The primary characteristic parameters of both Haloxylon ammodendron and the simulation models are presented in .

1.2 Experimental Equipment

Wind tunnel simulations were conducted at the "Wind-Sand Environment Wind Tunnel Laboratory" of the Gansu Desert Control Research Institute. The facility is a blow-type wind tunnel with a test section length of 16 m and a cross-section of 1.2 m × 1.2 m, featuring adjustable wind speeds from 4 to 35 $\mathrm{m \cdot s^{-1}}$. Wind pressure was measured using Pitot tubes and converted via a micro differential pressure sensor. The experimental setup enabled comprehensive flow field characterization under controlled conditions.

1.3 Windbreak Design

Three stand densities were established, corresponding to plant spacing configurations with density ratios of A = 93.0%, B1 = B2 = 46.5%, and C = 23.2%. The four planting point arrangements (A, B1, B2, and C) were configured in a "品" (pin) shape pattern, with specific plant spacing × row spacing dimensions as follows: A: 17 cm × 17 cm, B1: 34 cm × 17 cm, B2: 17 cm × 34 cm, and C: 34 cm × 34 cm. These designs correspond to field spacing of approximately 2.5 m × 2.5 m, 5.0 m × 2.5 m, 2.5 m × 5.0 m, and 5.0 m × 5.0 m, respectively, with actual planting densities of about 1500, 750, 750, and 375 $\mathrm{plants \cdot hm^{-2}}$, and canopy coverages of approximately 28.5% for all configurations. A schematic diagram of the windbreak designs is shown in [Figure 1: see original paper].

1.4 Wind Speed Measurement

The flow field characteristics of windbreaks are primarily influenced by individual plant architecture, group porosity, and windbreak width, with relatively minor influence from wind speed itself. Therefore, a moderate wind speed of 10 $\mathrm{m \cdot s^{-1}}$ was selected as the control condition. Along the wind tunnel centerline, measurement points were arranged at 20 cm intervals within a range of 13 cm before and 60 cm after the windbreak, covering heights of 13 cm, 20 cm, 30 cm, and 40 cm. The measurement point distribution is illustrated in [Figure 2: see original paper]. Horizontal wind speeds (U) were measured at each point, with 30 instantaneous wind speed readings recorded over approximately 1 minute and averaged. Wind speeds measured without plants served as the control (U_0).

1.5 Data Analysis

A 2.4 cm thick rough-surfaced wooden board with streamlined edges was installed in the wind tunnel test section to ensure smooth airflow transition without boundary layer separation. In the absence of plant models, the mainstream wind speed reached 24 cm height, establishing a boundary layer thickness of 24 cm. The simulation plant models (20 cm height) were positioned within this boundary layer, satisfying wind tunnel experimental requirements. Plant models were fixed to the board by drilling holes at their base positions.

Measured wind speeds with windbreaks (U) and without windbreaks (U_0) were normalized to obtain relative wind speed (U/U_0). Contour maps of relative wind speed were generated using Surfer software (Golden Software, USA), where $U/U_0 > 1$ indicated wind acceleration zones and $U/U_0 < 1$ indicated wind deceleration zones. Windbreak efficiency was quantified as wind speed reduction, calculated by: $(U_0 - U)/U_0 \times 100\%$. Positive values indicated wind speed reduction, while negative values indicated wind speed increase.

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2 Results

2.1 Flow Field Structure

The flow field near plants can be divided into several distinct regions: incoming flow zone, front deceleration zone, upper acceleration zone, side acceleration zones, rear deceleration zone, and recirculation zone. Due to the windbreak width being substantially larger than individual plants, the flow field structure was significantly modified. Analysis using relative wind speed (U/U_0) contour maps revealed that all four windbreaks created wind acceleration zones ($U/U_0 > 1$) approximately 40 cm before, above, and within the canopy, while wind deceleration zones ($U/U_0 < 1$) formed above and behind the canopy.

The area of wind speed deceleration zones accounted for 78.06%, 70.41%, 74.36%, and 82.80% of the total flow field area for configurations A, B1, B2, and C, respectively. Among the three windbreaks with equal plant spacing, the B1 windbreak (34 cm × 17 cm) exhibited a smaller deceleration zone area compared to B2 (17 cm × 34 cm), indicating that windbreaks with equal row and plant spacing produce more extensive deceleration zones than those with unequal spacing. The A windbreak demonstrated the most pronounced deceleration effect, with the weak wind zone ($U/U_0 < 0.4$) reaching 22.46% of the total flow field area, while the C windbreak showed the largest deceleration zone area but the least pronounced speed reduction, with its weak wind zone comprising only

5.91%. The B1 windbreak' s weak wind zone was merely 0.73% of the total area.

2.2 Wind Speed Variation

To characterize wind speed changes at different heights, we analyzed average wind speeds at three levels: above canopy (40 cm), within canopy (20-30 cm), and below canopy (13 cm). Statistical analysis revealed distinct patterns across these layers.

Above Canopy (40 cm): All four windbreaks maintained wind speeds around 11 $\mathrm{m \cdot s^{-1}}$ with minimal fluctuation. As airflow approached the windbreaks, speeds remained relatively stable, showing slight increases when flowing over the canopy before gradually decreasing. The overall variation was small and trends were consistent across all configurations.

Within Canopy (20-30 cm): When airflow reached the highest density A windbreak, speed decreased dramatically from 11 $\mathrm{m \cdot s^{-1}}$ to approximately 2.7 $\mathrm{m \cdot s^{-1}}$ at the first row, then remained low through the windbreak before gradually recovering. For the lowest density C windbreak, wind speed initially increased then decreased, stabilizing at 6-6.5 $\mathrm{m \cdot s^{-1}}$. For windbreaks B1 and B2 with equal density but different configurations, wind speed variation trends and magnitudes differed substantially: B1 showed an initial increase followed by decrease, while B2 exhibited a decrease then increase pattern, though post-windbreak recovery trends were similar.

Below Canopy (13 cm): After entering the windbreaks, airflow velocity initially increased then decreased in all configurations. The maximum wind speed for A windbreak occurred near the 8th row within the windbreak, while for C windbreak it appeared 20H behind the windbreak. Higher stand density resulted in smaller average wind speeds below the canopy but faster recovery of near-surface wind speeds behind the windbreak. The minimum wind speed points were located progressively closer to the windbreak with increasing density: 11H for A, 15H for B1 and B2, and 20H for C.

Post-windbreak wind speed recovery exhibited two key characteristics: (1) higher density produced greater wind speed reduction but faster recovery, and (2) at 40H behind the windbreak, wind speeds became consistent across all configurations, with below-canopy speeds approximately 10 $\mathrm{m \cdot s^{-1}}$ and minimal variation.

2.3 Wind Speed Reduction

To analyze spatial heterogeneity in windbreak efficiency, we calculated wind speed reduction along the wind direction at three heights (40 cm, 20-30 cm, and 13 cm). At 40 cm height, wind speed reduction remained below 10% both before and after the windbreaks. At 20-30 cm height, all windbreaks showed negative reduction values (indicating acceleration) before the windbreak, which increased substantially upon entering the windbreak. For A windbreak, reduction immediately reached 60–80% and remained stable until 15H before declining. B2 windbreak showed 40–60% reduction post-windbreak, while B1 and C exhibited lower overall reduction values.

At 13 cm height, wind speed reduction patterns were most pronounced. The A windbreak achieved over 60% reduction, with the maximum reduction occurring at the same position as at 20–30 cm height. Overall, higher stand density yielded better windbreak efficiency, with the ranking A > B2 > B1 > C.

The near-surface layer (below 20 cm) is critical for understanding surface erosion-deposition processes and microtopography formation. Average wind speed reduction in this layer showed that wind speeds increased slightly before the windbreaks (negative reduction values). The primary windbreak effect occurred behind the windbreaks, where A, B1, B2, and C windbreaks achieved average reductions of 63.15%, 35.86%, 38.66%, and 24.37%, respectively, following the ratio A:B:C   6:3:2.

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3 Discussion

Stand density is closely related to windbreak efficiency. For Haloxylon ammodendron forests, individual plant geometry and spatial architecture are consistent, making stand density the key structural factor. This study demonstrated that reduced stand density weakened wind speed attenuation and decreased windbreak efficiency, primarily because lower density substantially reduced the foliage available for dissipating airflow energy. However, the relationship was not strictly proportional: when density decreased from A to B (50% reduction), near-surface wind speed reduction behind the windbreak decreased to approximately 60% of the original value, but when density halved again from B to C, reduction only decreased to about 64% of the B level. This indicates a nonlinear relationship between wind speed reduction rate and stand density, where density changes affect windbreak efficiency more significantly at higher density ranges.

Planting point configuration significantly influences airflow pathways. While stand density or porosity controls the volume of airflow entering and passing over the windbreak, planting pattern guides the path of airflow through the windbreak, determining momentum absorption and locally accelerating or decelerating airflow. When airflow enters perpendicular to the windbreak, rectangular configurations create direct through-channels, whereas pin-shaped configurations create network flow paths. This network pattern enhances turbulence intensity within the windbreak, increasing energy dissipation. Therefore, in establishing windbreak and sand fixation forests, the pin-shaped configuration should be prioritized.

The combined effects of density and configuration have important practical implications. Current initial planting densities for Haloxylon ammodendron in China's sandy regions typically range from 833 to 1666 plants$\cdot$hm^{-2}. This study considered natural thinning during stand development and soil water carrying capacity in rain-fed Haloxylon ammodendron forests, with the three tested densities representing initial planting density, post-thinning density under rain-fed conditions, and natural stand density. Without considering individual growth changes, results indicate that initial planting density provides the best windbreak efficiency, with rain-fed thinned stands achieving about 60% of the initial density' s effectiveness, still superior to natural stands. These findings guide density management during afforestation and silvicultural practices and enable evaluation of windbreak efficiency for different pin-shaped configurations.

4 Conclusions

Wind tunnel simulation experiments examining flow field and windbreak efficiency under varying density and planting point configurations yielded the following main conclusions:

1. The wind speed deceleration zone areas accounted for 78.06%, 70.41%, 74.36%, and 82.80% of the total flow field area for configurations A, B1, B2, and C, respectively. Higher stand density created larger weak wind zones ($U/U_0 < 0.4$). For windbreaks with equal density, the distribution and intensity of acceleration and deceleration zones varied with planting point configuration.
2. Above-canopy wind speeds remained around $11\ \text{m} \cdot \text{s}^{-1}$ with consistent trends across all configurations. Within the canopy, the A windbreak showed the most dramatic speed reduction, with minimum wind speed of approximately $2\ \text{m} \cdot \text{s}^{-1}$. Below-canopy airflow initially increased then decreased, with maximum wind speed occurring near the 8th row for A windbreak and at 20H behind the C windbreak. Higher stand density resulted in lower average wind speed below canopy but faster near-surface wind speed recovery behind the windbreak, with minimum wind speed points located progressively closer to the windbreak.
3. At 13 cm height, wind speed reduction varied significantly along the wind direction, with maximum reduction consistent with that at 20–30 cm height. Overall, higher density yielded better windbreak efficiency, with the ranking A > B2 > B1 > C. The relationship between windbreak efficiency and stand density was nonlinear, with near-surface wind speed reduction ratios of A:B:C   6:3:2 behind the windbreaks.

In practice, afforestation density should be determined based on soil water carrying capacity, with priority given to pin-shaped configurations featuring "small plant spacing, large row spacing."

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