Comparative study on windbreak effects of two different configuration shelterbelts

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Abstract. Pinus sylvestris, Artemisia ordosica, Tamarix chinensis Lour, Elaeagnus angustifolia and Salix matsudana Koidz were selected to design the models of forest belts. Through wind tunnel experiments, we analyzed the wind speed frequency, wind speed flow field and wind protection efficiency of two different configuration shelterbelts. The results showed the wind speed frequency of mixed shelterbelts was generally lower than that of single shelterbelts with the same configuration. The similarity of the average wind speed between No.1 A3 and No.2 C3 indicates that the windbreak effect of low-density arbor-shrub mixed shelterbelt was similar to that of high-density single shelterbelt. The average wind protection efficiency of No.1 A1 was similar to that of No.1 C2, indicating that the influence of density of pinus sylvestris of wind protection efficiency is greater than the height of forest belt. the average wind protection efficiency of No. 2 A2 was 57.64%, which was similar to that of No. 2 B3, indicating that the height of the forest belt increased, and the influence of density on the protection effect of the forest belt decreased. Therefore, the wind protection ability of multi-species and highly hierarchical mixed forests was higher than that of single shelterbelt.

Keywords: Arbor-shrub mixed forest shelterbelt, single arbor forest, wind tunnel experiment, windbreak effect, different configurations

1. Introduction

Frequent wind and sand disasters and expanding desertified land have become important environmental problems in arid and semi-arid areas. Shelterbelt is an important part of the vegetation ecosystem in arid and semi-arid areas [1]. It affects the flow field structure of the forest belt by changing airflow velocity and direction, to reduce wind speed and control quicksand [2]. It plays an important role in improving the ecological environment of oases, protecting biodiversity, and promoting sustainable social and economic development [3–4].

The protective benefit of a shelterbelt is closely related to the spatial structure of the shelterbelt and the selection of tree species [5]. At present, domestic and foreign scholars have used cluster analysis, analytic hierarchy process, goal programming model and other research methods to study the spatial allocation of Populus alba Linn. var. pyramidalis Bunge, Fraxinus mandschurica Rupr., Populus nigra Linn. var. thevestina (Dode) Bean, Haloxylon ammodendron (C.A. Mey.) Bunge, Salix
myrtilloides var. mandshurica Nakai, Tamarix chinensis Lour., Hippophae rhamnoides Linn. and other shelterbelts with pure forest or broad-leaved Arbor shrub mixed forest [6–7]. It is confirmed that different densities, height and tree species affect the cross-sectional structure and permeability of the shelterbelt, which makes significant differences in the flow field structure, protective distance and effective protective area of different shelterbelts. Scientific and rational spatial allocation can maximize the ecological and economic benefits of shelterbelts.

However, most shelterbelts were composed of tall broad-leaved tree species with a short life, such as Populus alba Linn. var. pyramdali., Salix matsudana Koidz. and fast-growing poplar, but water resources are scarce in arid sandy areas, and the survival rate and preservation rate of tall Arbor forest cannot be guaranteed. Its long-term wind protection capacity is rarely evaluated. Arbor-shrub mixed forest is mostly a mixture of single tree and shrub [8]. There is little research on multi-species and high-benefit Arbor-shrub mixed windbreak and sand fixation forest. In this study, Pinus sylvestris Linn. var. mongolica Litv., Artemisia ordosica, Tamarix chinensis Lour., Elaeagnus angustifolia Linn. and Salix matsudana Koidz. were selected as the research objects, and the wind speed changes and effective protective area of single forest belt and multi-species mixed forest belt were compared by wind tunnel simulation test, to provide new ideas for the configuration optimization of the shelterbelts.

2. Materials and Methods

2.1 Experimental Equipment

The wind protection experiment was conducted in the Wind Sand Physics Laboratory of Beijing Forestry University. The wind tunnel is 24 m long, the main test section is about 12 m long, and the cross-sectional area is 0.6×0.6 m. The thickness of the boundary layer of the wind tunnel restricts the size of the model. The thickness of the bottom boundary layer of the experimental section of the wind tunnel is about 0.25 m, which is larger than the forest belt model, which meets the requirement that the experimental model must be contained within the boundary layer of the wind tunnel. The boundary layer on the sidewall of the wind tunnel affects the quality of the flow field in the tunnel. The thickness of the boundary layer on the side of the wind tunnel is 0.05 m, i.e., the wind speed is balanced and stable within a width of 0.25 m on the left and right of the wind tunnel’s central axis [9]. The minimum wind speed of the wind tunnel can be set to 3 m/s, the maximum wind speed can be set to 42 m/s, and the effective test section wind speed pulsation is less than 1.5% [10].

2.2 Shelterbelts Design

In wind tunnel simulation experiments, the most important thing is to ensure that the model meets the requirements of geometric similarity [11], i.e., the model and the entity configuration are identical and proportional. The use of dimensionless physical quantities in the experiment ensures that when analyzing the relationship between research results, the physical quantities themselves are no longer examined, but the values of physical quantities can be compared. Based on the above criteria, and accounting for the influence of the wind tunnel boundary layer on the experimental accuracy, the configuration parameters of Pinus sylvestris, Artemisia ordosica, Tamarix chinensis Lour, Elaeagnus angustifolia and Salix matsudana Koidz of 5 years, 10 years, and 20 years were taken as reference to design the models according to the scale of 1:100 (The height of each model was shown in Table 1). According to different row spacing, three heights of forest belt models were ordered into 10 rows and 3 groups of forest belts with different configuration types. Among them, the spacings between the rows of arbors were 2 cm×2 cm, 4 cm×4 cm, and 6 cm×6 cm, the row spacings between arbor and shrub were 2 cm×2 cm+2 cm×2 cm, 4 cm×4 cm+3 cm×3 cm, and 6 cm×6 cm+4 cm×4 cm, respectively. The bases of the shelterbelt models were fixed on a high-strength, high-toughness thermoplastic (ABS) board with a thickness of 3 mm. In order to ensure the stability of the airflow and to reduce the separation of the frontal surface layer caused by the thickness of the bed surface, blank ABS
boards of equal thickness were laid before and after the forest belt during the experiment. Part of the experimental models were shown in Figure 1.

### Table 1. Parameters of the forest belts model with different configurations

| Forest Type | Forest Number | Rows | Length, cm | Width, cm | Height, cm | Row spacing, cm | Line spacing, cm |
|-------------|---------------|------|------------|-----------|------------|----------------|-----------------|
| *Pinus sylvestris* var. *mongolic* forest belt | 1 A1 | 10 | 60 | 18 | 1 | 2 | 2 |
| | 1 A2 | 10 | 60 | 18 | 4 | 2 | 2 |
| | 1 A3 | 10 | 60 | 18 | 20 | 2 | 2 |
| | 1 B1 | 10 | 60 | 36 | 1 | 4 | 4 |
| | 1 B2 | 10 | 60 | 36 | 4 | 4 | 4 |
| | 1 B3 | 10 | 60 | 36 | 20 | 4 | 4 |
| | 1 C1 | 10 | 60 | 54 | 1 | 6 | 6 |
| | 1 C2 | 10 | 60 | 54 | 4 | 6 | 6 |
| | 1 C3 | 10 | 60 | 54 | 20 | 6 | 6 |
| *Artemisia ordosica* + *Tamarix chinensis* Lour + *Elaeagnus Angustifolia* + *Salix matsudana* Koidz + *Pinus Sylvestris* var. *mongolic* | 2 A1 | 10 | 60 | 18 | 4 | 2 | 2 |
| | 2 A2 | 10 | 60 | 18 | 6 | 2 | 2 |
| | 2 A3 | 10 | 60 | 18 | 20 | 2 | 2 |
| | 2 B1 | 10 | 60 | 33 | 4 | 3(shrub); 4 (arbor) | 3(shrub); 4 (arbor) |
| | 2 B2 | 10 | 60 | 33 | 6 | 3(shrub); 4 (arbor) | 3(shrub); 4 (arbor) |
| | 2 B3 | 10 | 60 | 33 | 20 | 3(shrub); 4 (arbor) | 3(shrub); 4 (arbor) |
| | 2 C1 | 10 | 60 | 48 | 4 | 4(shrub); 6 (arbor) | 4(shrub); 6 (arbor) |
| | 2 C2 | 10 | 60 | 48 | 6 | 4(shrub); 6 (arbor) | 4(shrub); 6 (arbor) |
| | 2 C3 | 10 | 60 | 48 | 20 | 4(shrub); 6 (arbor) | 4(shrub); 6 (arbor) |

#### 2.3 Wind Speed Observation

In order to ensure similar dynamics, the experiment took the Ulan Buh Desert Yellow River section as the experimental environment prototype. Using sharp wedges and rough elements, the simulated wind environment in the wind tunnel was adjusted to be consistent with the wind speed profile equations of the 48 m high wind flux tower in the Ulan Buh desert wilderness. Under the experimental conditions, the frictional wind speed was 0.48 m/s, and the minimum Reynolds number was \(4.8 \times 10^5\), which met the conditions of Reynolds number independence [12].

Due to different widths of the shelterbelt models, the forest belts were fixed at the same position during wind speed observation, so that the position of the first row of the leeward side of each configuration of the forest belts was consistent (Fig.1). The wind speed of the experiment was the axial wind speed of 12 m/s. The measurement range of wind speed was the area of a fixed rectangle behind the belt. The length of the rectangle was 0–110 cm behind the forest belt, and the width was the central axis of the wind tunnel extending to both sides to 25 cm. There were a total of 99 observation points, distributed in a grid pattern, with a vertical interval of 10 cm and a horizontal interval of 5 cm. In order to facilitate the comparison between the experimental results and the measured values in the field, the measurement height was set to 2 cm. The wind speed data at the measurement points were obtained through the KIMO VT200 hot-wire anemometer and the three-dimensional migration measurement system, and the comparison wind speed was the wind...
speed under the empty wind tunnel at each observation point.

2.4 Windproof Efficiency
Windbreak efficiency is an important indicator that reflects the protection ability of forest belts. It refers to the percentage of the average wind speed at the observation point lower than the wind speed in the open field. The calculation formula is:

$$E_{hz}=\frac{V_{fz}-V_{hz}}{V_{fz}}*100\%,$$

where $E_{hz}$ is the windproof efficiency; $V_{fz}$ is the average wind speed at height $Z$ in the open field; $V_{hz}$ is the average wind speed at height $Z$ at the distance between $h$ and the forest belt.

3. Results
3.1 Statistical analysis of wind speed
As shown in Table 2, the 20-year high-density No. 2 A3 had the lowest average wind speed of 2.68 m/s, while the 5-year high-density No. 1 C1 had the highest average wind speed of 8.77 m/s. The average wind speed of No. 2 A2 was similar to that of No. 2 B3, indicating that the windbreak effect of high shelterbelt was similar to that of dense shelterbelt. The similarity of the average wind speed between No. 1 A3 and No. 2 C3 indicates that the windbreak effect of low-density Arbor-shrub mixed shelterbelt is similar to that of high-density Arbor single shelterbelt.

The frequency histogram of wind speed can reflect the concentration and variability of the wind speed distribution in shelterbelt. As can be seen from Figure 2, the structure of the wind speed frequency curve of different shelterbelts was similar, the frequency was relatively concentrated, and the extreme value was less, which was consistent with normal distribution. In the Pinus sylvestris of No. 1 shelterbelt, the wind speed frequencies of A1, B2 and C2 were mostly distributed in 7.5–8.5 m/s, and the wind speed frequencies of B1 and C1 were mostly distributed in 8–9 m/s. In the mixed forest of No. 2, the wind speed frequencies of B1 and C1 were 7–8 m/s, the wind speed frequency of C2 was 5–7 m/s, the wind speed frequencies of B2 and C3 were 4–5 m/s. It can be seen that the wind speed frequency of mixed shelterbelt was generally lower than that of single shelterbelt with the same configuration. In statistics, skewness is an indicator of the degree of asymmetry of data relative to the average, and kurtosis is an index of the concentration of data distribution or the sharpening degree of the distribution curve. In the Pinus sylvestris of No. 1 shelterbelt, A3, B3, C1 and C3 were
positively skewed, while others were negatively skewed. In the mixed forest of No. 2, the 5-year-old forest belt and the low-density 10-year-old forest belt were negative skewness, while the other shelterbelts were positive skewness. By comparing the kurtosis of each group, B3, C1 and C3 were low broad peaks, and the others were high and narrow peaks in No. 1 shelterbelt. The kurtosis change of the wind speed frequency of No. 2 shelterbelts was small, whereas the wind speed of the high-density shelterbelts was more concentrated, which were high and narrow peaks, while the No. 2 C3 low-density shelterbelts had low broad peak (Table 2).

Figure 2. Frequency histograms of forest belts in different configurations: (a) Histogram of frequency of wind speed in differently configured forest belts in No.1; (b) Histogram of frequency of wind speed in differently configured forest belts in No.2

Table 2. Statistical parameters of wind speed distribution of the forest belt model in different configurations
The velocity contour line of No. 1 shelterbelt C2, indicating that when the shelterbelt protection effect was good.

The high forest belt on the airflow was more obvious, which made the reduction of the wind speed the latter No. 2 A2 was 20 cm behind the belt, and the wind speed increased at a constant speed.

As shown in Figure 3, with the same density, the wind speed decreased at the same position, the wind shadow areas moved backward, and the airflow moves more regularly in the forest shelterbelt. And the density of the shelterbelt increased, the wind speed decreased. The wind speed reduction of the high-density shelterbelts with 20 years old was the most obvious. However, the low-density shelterbelts with 5 years old had the worst wind protection effect.

Among them, the wind speed flow field of the No. 1 shelterbelt formed several wind speed acceleration zones, and the windbreak effect was much less than that of the No. 2 belt, which was due to the low and sparse shelterbelt and its limited ability to reduce wind speed. The equal wind speed line behind the No.1 A2 forest belt was almost parallel to the direction of the forest belt, and the wind speed increased at a constant speed. In the No. 2 shelterbelts, the wind speed of the high-density shelterbelts decreased sharply, forming a wind shadow area. The wind shadow area of No. 2 A2 was 20–40 cm behind band, and the wind shadow area of A3 was 40–70 cm, and the area of the latter was larger than that of the former. This was because the cutting and blocking effect of the high forest belt on the airflow was more obvious, which made the reduction of the wind speed behind the belt more intense. The velocity contour line of No. 2 C2 was roughly parallel to the direction of the forest belt, and there was no obvious wind shadow area, and the wind speed between 0–50 cm behind the belt was less than 66.67 % of the control wind speed, indicating that the protection effect was good. The minimum wind speed behind No. 1 A1 belt was similar to that of No. 1 C2, indicating that when the shelterbelt height was limited, properly increasing the density of the shelterbelt could also improve the windbreak effect of the shelterbelt.

| Type | Samples | $U_{\text{max}}$, m/s | $U_{\text{min}}$, m/s | Average value±Standard Error | Standard Deviation | Kurtosis | Skewness | Coefficient of Variation, % |
|------|---------|----------------------|---------------------|-----------------------------|-------------------|----------|----------|----------------------------|
| 1 A1 | 99      | 8.8                  | 6.81                | 8.06±0.04                   | 0.42              | -0.14    | -0.63    | 5.25                       |
| 1 A2 | 99      | 8.31                 | 3.02                | 6.16±0.14                   | 1.42              | -0.74    | -0.62    | 23.01                      |
| 1 A3 | 99      | 5.51                 | 1.67                | 3.19±0.11                   | 1.11              | -1.08    | 0.40     | 34.93                      |
| 1 B1 | 99      | 9.01                 | 8.01                | 8.56±0.02                   | 0.23              | -0.80    | -0.16    | 2.64                       |
| 1 B2 | 99      | 8.37                 | 6.18                | 7.43±0.06                   | 0.56              | -0.85    | -0.41    | 7.55                       |
| 1 B3 | 99      | 6.76                 | 4.58                | 5.14±0.04                   | 0.44              | 1.74     | 1.33     | 8.54                       |
| 1 C1 | 99      | 9.23                 | 8.26                | 8.77±0.02                   | 0.19              | 0.01     | 0.24     | 2.15                       |
| 1 C2 | 99      | 8.63                 | 7.02                | 7.98±0.04                   | 0.35              | -0.33    | -0.47    | 4.42                       |
| 1 C3 | 99      | 8.22                 | 6.09                | 6.71±0.04                   | 0.35              | 6.02     | 2.02     | 5.25                       |
| 2 A1 | 99      | 8.33                 | 1.76                | 5.56±0.20                   | 2.02              | -1.11    | -0.53    | 36.41                      |
| 2 A2 | 99      | 7.58                 | 1.07                | 3.81±0.20                   | 1.97              | -1.33    | 0.16     | 51.63                      |
| 2 A3 | 99      | 5.04                 | 0.82                | 2.68±0.13                   | 1.31              | -1.33    | 0.20     | 48.72                      |
| 2 B1 | 99      | 8.29                 | 4.63                | 7.01±0.09                   | 0.89              | -0.20    | -0.80    | 12.73                      |
| 2 B2 | 99      | 7.22                 | 3.08                | 5.10±0.12                   | 1.17              | -1.27    | 0.14     | 23.02                      |
| 2 B3 | 99      | 5.88                 | 2.47                | 3.93±0.09                   | 0.92              | -0.88    | 0.33     | 23.30                      |
| 2 C1 | 99      | 8.43                 | 5.45                | 7.54±0.06                   | 0.56              | 0.87     | -0.85    | 7.45                       |
| 2 C2 | 99      | 7.76                 | 4.31                | 6.09±0.08                   | 0.83              | -1.06    | -0.05    | 13.60                      |
| 2 C3 | 99      | 6.13                 | 3.09                | 4.54±0.06                   | 0.55              | 0.10     | 0.55     | 12.14                      |

3.2 Distribution characteristics of the wind speed flow field

As shown in Figure 3, with the same density, the height of the shelterbelt increased, the wind speed decreased at the same position, the wind shadow areas moved backward, and the airflow moves more regularly in the forest shelterbelt. And the density of the shelterbelt increased, the wind speed decreased. The wind speed reduction of the high-density shelterbelts with 20 years old was the most obvious. However, the low-density shelterbelts with 5 years old had the worst wind protection effect.
Figure 3. Wind speed flow field of single forest belts in different configurations: (a) Wind speed flow field in differently configured forest belts in No. 1; (b) Wind speed flow field in differently configured forest belts in No. 2

3.3 Wind protection efficiency
In terms of the average wind protection efficiency, the wind protection efficiency of the high-density shelterbelt was higher than that of the medium- and low-density shelterbelt. The average wind protection efficiency of No. 2 A3 was 66.48 %, followed by that of No. 1 A3, which was 64.57 %. The average wind protection efficiency of No. 1 A1 was similar to that of No. 1 C2, indicating that the influence of the density of *Pinus sylvestris* on the wind protection efficiency is greater than the height of the forest belt. The wind protection efficiency of No. 1 A3 belt first increased and then decreased, the maximum windproof efficiency appeared at 60 cm behind the belt, which was 81.26 %,
and the minimum wind protection efficiency appeared at 10 cm behind the belt, which was 38.78 %. The wind protection efficiency of No. 1 B3 and No. 1 C3 shelterbelts increased gradually with distance, which was due to the fact that the barrier of the high shelterbelt forced the air flow to rise and prolonged the distance of wind speed recovery behind the belt. In the No. 2 shelterbelt, the average wind protection efficiency of No. 2 A2 was 57.64 %, which was similar to that of No. 2 B3, indicating that the height of the forest belt increased, and the influence of the density on the protection effect of the forest belt decreased.

Figure 4. Wind protection efficiency of Coniferous-broad mixed forest belts in different configurations: (a) Wind protection efficiency of different configuration forest belts in No. 1; (b) Wind protection efficiency of different configuration forest belts in No. 2
4. Discussion
The wind protection efficiency of shelterbelts is governed by many factors, such as individual characteristics of tree species [13], shelterbelts density [14], height [15], and the distribution pattern [16–17]. The geometric shape and spatial structure of the plant determine that the shelterbelts composed of different tree species have different effects on air flow. With the increase of tree growth and the height of the shelterbelt, the crown width and the number of branches and leaves change, resulting in a more complex structure of the shelterbelt, and there are significant differences in the windbreak efficiency of different shelterbelts. In this paper, the wind protection efficiency of the arbor-shrub mixed forest belt and the single shelterbelt under different height and density patterns were compared and analyzed. Most shelterbelts had calm wind areas with different areas on the leeward side, which was due to the rapid sinking of the air flow on the leeward side of the shelterbelt. The average wind speed of No. 2 A3 was the lowest, which was 2.68 m/s, followed by No. 1 A3, No. 2 A2 and No. 2 B3, respectively. The average wind speed of No. 1 C1 was the highest, which was 8.77 m/s, followed by No. 1A1 and No. 2 C1, respectively. The average wind speed of the mixed forest was lower than that of the single shelterbelt, and the wind protection ability of the 20-year old high-density forest was the strongest. The low shelterbelt was highly variable, which was due to the fact that the shelterbelt was low and sparse, resulting in limited ability to reduce wind. The area and intensity of the wind shadow area increase behind the high forest belt, indicating that the cutting and blocking effect of the high forest belt on air flow was more significant, but the wind speed of some tall dense forest belts recovered quickly. Among them, the coefficient of variation of No. 2 A2 was the largest, which was 51.63 %, and the coefficient of variation of other shelterbelts was less than 50 %. The wind speed variation of the high-density forest belt was larger than that of the medium and low-density forest belts, which showed that the high-density forest belt could obviously reduce the wind speed. In the shelterbelt composed of the same tree species, the higher the tree height was, the more stable the air flow behind the belt was, and the smaller the wind speed in the same position was, which was consistent with the conclusion of Ma Yanjun et al. In the shelterbelts with the same height, the wind reduction ability of the forest belt increased with an increase in the density, which was consistent with the research conclusions of Bitog et al. [18] and Cheng et al. [19]. The average wind protection efficiency of No. 1 A1 is equivalent to that of No. 1 C2, and the average wind protection efficiency of No. 2 A2 is similar to that of No. 2 B3, indicating that when the shelterbelt height was limited, the density of the shelterbelt was an important factor affecting the wind protection efficiency of the shelterbelt, and the density advantage of the shelterbelt was weakened, and a better protective effect could be obtained by properly reducing the density of the shelterbelt. In addition, the wind speed acceleration in the vertical direction of the shelterbelt could directly reflect the airflow acceleration by the shelterbelt [20]. The change of the vertical wind speed in the shelterbelt was not observed in this experiment, which has led to some limitations in the comparison results. In the future, it will be reasonable to add the wind speed behind the vertical belt in our test in order to enrich the test results.

5. Conclusion
(1) The wind protection ability of multi-species and highly hierarchical mixed forests was higher than that of the single shelterbelt. The wind speed behind the shelterbelt of mixed forests was generally lower than that of the same configuration of arbor forest belts.

(2) The height of the shelterbelt increased, the wind shadow area moved backward, and the wind protection efficiency area increased. As the height of the shelterbelt increased, the influence of density on the wind protection efficiency of the shelterbelt decreased. The wind protection efficiency of the 10-year old high-density mixed shelterbelt was similar to that of the 20-year old low-density shelterbelt.

(3) The density of shelterbelt was the main factor affecting the windbreak ability of 5-year-old and 10-year-old shelterbelts. The wind protection efficiency of 5-year-old and 10-year-old shelterbelts
increased with an increase in the density. The coefficient of variation of high-density shelterbelt was the largest, which was not conducive to the growth of vegetation. The wind protection efficiency of the low-density arbor-shrub mixed shelterbelt was similar to that of the high-density single shelterbelt.

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