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RESEARCH ARTICLE

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Field investigation on *Salix psammophila* plant morphology and airflow structure

Abstract The field investigation was undertaken to determin the characteristics of *Salix psammophila* plant morphdogy and airflow structure of single-line *S. psammophila* on the southern edge of the Mu Su sandland. The results showed that artificially cultivated single-line *S. psammophila* could accumulate sand because the plant decreased the windward and leeward wind velocity. There was a significant correlation (R = 0.696) between accumulated sand volume (V_2) and plant volume (V_1). The wind velocity was 6 m/s at a 4 m height of single-line *S. psammophilahedge* row. The wind velocity decreased at 3 H windward and increased at 2 H to windward. The wind velocity then steeply decreased to leeward and reached its lowest value at 1 H to leeward and gradually recovered to the open field velocity. The protection distance of the single-line *S. psammophila* was about 17 H' and the effective protection distance was about 13 H'. Single-line *S. psammophila* had few effects on the wind velocity when the wind was above the plant height.

Keywords shrub, plant morphology, flow structure, wind erosion-preventing effect, *Salix psammophila*

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1 Introduction

Vegetation plays an important role in the prevention of wind erosion and sand fixation, covering the ground surface, reducing wind forces, and preventing the transport of large amounts of sand, etc (Bressolier and Thomas, 1979; Van et al., 1989; Wolfe and Nickling, 1993; Wolf and Nicking, 1996). The effects of various plants in sand fixation and preventing wind erosion are taken into account as much as possible in selecting and collocating plant species in eco-environmental rehabilitation projects (Zhou and Zhu, 1994). A number of studies in agricultural afforestation have been carried out during the last 50 years (Van et al., 1989). Up to now, the results of much research have accumulated from field investigations (Dong et al., 1983; Guan et al., 1996; Liu et al., 1997; Grant and Nicking, 1998; Yue et al., 2004), wind tunnel experiments (Zhang, 1984; Guan and Zhu, 2000) and regional control practices (Zhu and Zhou, 1993; Guan et al., 2001; Jin, 2001; Li et al., 2003).

Many investigations of the ecological effects of trees and assessment methods have been made in China (Wei, 1987; Schwartz et al., 1995; Zhou et al., 1995; Wu, 2003). Due to their limited requirements for water and nutrients, shrubs have a stronger adaptability than trees in arid and semi-arid lands and contribute more to the eco-environment (Zhang, 1994; Xu and Xu, 1996). From shrub research, field investigation data were mainly obtained by using portable wind speed instruments that could only, in a cursory way, evaluate the wind erosion-preventing effect of shrubs (Lee, 1991; Liao et al., 1995; Huang and Gao, 2001; Zhang et al., 2004). Therefore, it is important that airflow structures of shrubs be established using the auto-collection data system of gradient wind.

In addition, plant morphology has an important influence on sand-fixing and wind erosion prevention effects of vegetation (Huang et al., 2002). The factor determining the sand-fixing and wind erosion prevention effects of vegetation is the area of the profile of the windward side of the plant which, in turn, is affected by plant height, crown diameter and porosity, etc. Little attention has been paid to plant morphology (Guan and Zhu, 2000; Zhu et al., 2004).

S. psammophila is a dominant community species in the Mu Su sandland. Usually, it appears scattered in the middle-base of dunes, especially on the leeward slope, or densely spread out in the bottomland mixed with *S. linearistripularis*. *S. psammophila* has economic and ecological value. The objectives of this study were to determine the characteristics of *S. psammophila* plant morphology and airflow structure of a single-line *S. psammophila* hedge row on the southern edge of the Mu Su sandland.

2 Materials and methods

2.1 Study area

The study was conducted in the dune-bottomland ecotone of the southern Mu Su sandland, approximately 23 km north of Jingbian County, Shanxi Province, with an elevation of 1,230 m. The climate is largely that of a temperate semi-arid monsoon area. The annual average temperature is 7.9°C, the mean annual precipitation 394.7 mm, and the average annual evaporation is 2,484.5 mm. The annual average wind speed is 2.9 m/s. The shear threshold velocity is 4.0 m/s and the number of days with wind speed > 4 m/s in March–May accounts for 50.2% of that in the whole year. Landforms are dominantly mobile, semi-mobile and fixed sandy dunes, flat sands, and lake-basin bottomland. Soil types are mobile aeolian sandy soils, fixed aeolian sandy soils, and meadow soils. The vegetation is that of warm-temperate belt grasslands. Plants adapted to the fixed and semi-fixed sandy dunes are dominant species and mainly composed of *Artemisia spherocephala*, *Agriophylium squarrosum*, *Corispermum puberulum*, and *Psammochloa villosa*.

2.2 Methods

In April 2004, 58 individual plants of an artificially cultivated single-line *S. psammophila* hedge row the flat sands were chosen in the study area (Fig. 1a). Their

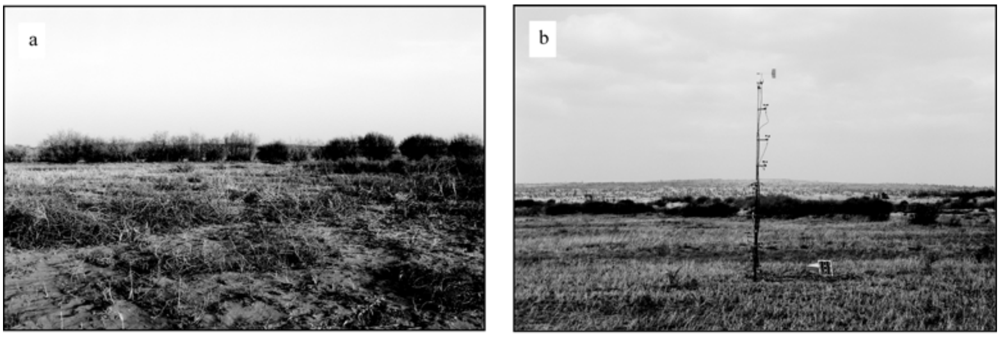

Fig. 1 Landscape of the observation site. a) Single-line *S. psammophila* in the flat sands, b) Auto-collection data system of gradient wind

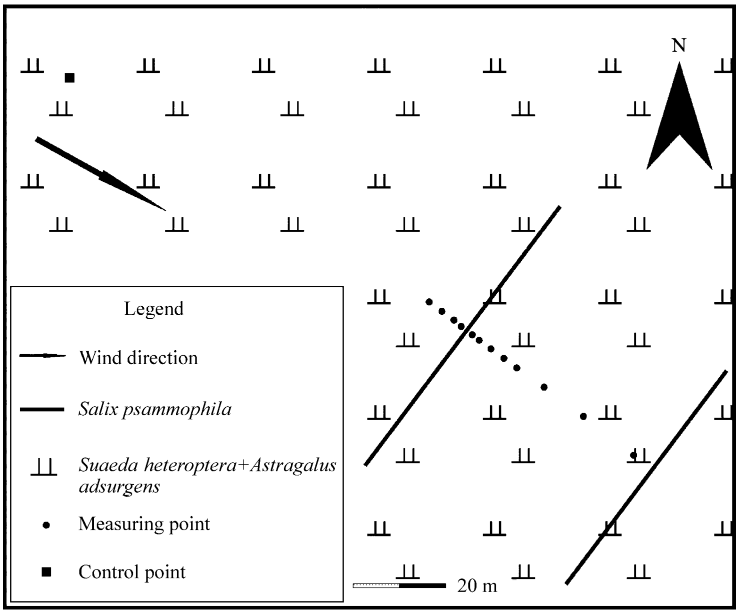

Fig. 2 Sketch map of the location of the observation site

morphological variables, including crown diameter (maximum diameter and the diameter perpendicular to it), plant height, diameter of accumulated sand (maximum diameter and its perpendicular diameter) and height of accumulated sand, were measured.

On 12 April (13:00–19:00), average 1-minute wind velocities at nine heights (0.32, 0.53, 0.71, 1.23, 1.50, 2.00, 2.50, 3.00, and 4.00 m) at measuring points (mobile instruments) and an anchor point in the open field (instruments fixed) were measured, using two sets of auto-collection data systems of gradient winds (Fig. 1b; instruments made by the Changchun National Meteorological Instrument Co.). Measuring points were located at 0.5, 1, 2, 3 H (H = 3.5 m, average plant height H'= 2.68 m) on the windward side of the single-line *S. psammophila* and at 0.5, 1, 2, 3, 4, 6, 9, 13 H on the leeward side (Fig. 2). It took 20–30 min at each measuring point to obtain the required information on wind speeds. Relative wind velocity is the ratio of average wind velocity at the measuring point to that of the anchor point in the open field corresponding to the same measurement time. The anchor point in the open field was 100 m from the single-line *S. psammophila* in the upwind direction, where the underlying surface was bare and without any barrier, to agree with that of the single-line *S. psammophila.* The single-line *S. psammophila* was 70 m in length and composed of 23 individual plants. The azimuth reading was 37° and porosity was 0.3. In a southeasterly direction was another line of *S. psammophila* with 17 individual plants. The distance between the two lines of *S. psammophila* was about 50 m. Around the test single-line *S. psammophila* were artificially cultivated *Astragalus adsurgens* shrubs, whose average plant height was 0.45±0.42 m (n = 51), and artificially cultivated *Suaeda heteroptera,* whose average plant height was 0.21±0.05 m (n = 18). Vegetation cover was about 15%. The main wind direction during the period of observation was 299° (looks more like 120° (see Fig.2)). The wind direction pulse was intense.

3 Results

3.1 Characteristics of plant morphology

Table 1 shows the statistical results of the morphological variables of *S. psammophila* plants. Plant volume of *S. psammophila* (V_1) was estimated using the volume formula of an ellipsoid sphere. The accumulated sand volume (V_2) was appraised using the volume formula of a hemi-ellipsoid sphere. For *S. psammophila* plants, the average maximum crown diameter (a_1), its perpendicular crown diameter (b_1), and plant height (H_1) were 4.00, 2.89, and 2.68 m. The maximum crown diameter was 6.00 m and the maximum height was 3.90 m. For the accumulated sand, the average maximum diameter (a_2) and its perpendicular diameter (b_2) and height (H_2) were 2.28, 1.66, and 0.28 m and the maximum height was 0.50 m. Among the individual plants were significant differences in plant volumes (V_1) and accumulated sand volumes (V_2). The maxima of plant volume and accumulated sand volume were 37 and 107 times their respective minima.

Table 1 Statistics of the morphological variables of *S. psammophila* plants

Valuable name	Maximum crown diameter a_1 /m	Crown diameter perpendicular to maximum diameter b_1 /m	Plant height H_1 /m	Maximum diameter of accumulated sand a_2 /m	Diameter of accumulated sand perpendicular to maximum diameter b_2 /m	Height of accumulated sand H_2 /m	Plant volume V_1 /m^3	Accumulated sand volume V_2 /m^3
Mean	4.00	2.89	2.68	2.28	1.66	0.28	147.03	2.61
Min.	1.60	1.00	1.60	1.20	0.90	0.05	14.07	0.12
Max.	6.00	6.00	3.90	4.10	3.00	0.50	519.98	12.87
Std. deviation	1.17	1.05	0.47	0.55	0.49	0.13	103.37	2.30
CV	0.29	0.36	0.18	0.24	0.29	0.45	0.70	0.88

$V_1 = (4/3)\pi a_1 b_1 H_1$; $V_2 = (2/3)\pi a_2 b_2 H_2$.

Table 2 shows the correlation coefficients of the morphological variables of *S. psammophila* plants. It can be seen that there was a significant correlation between maximum crown diameter (a_1) and maximum diameter of accumulated sand (a_2); the correlation coefficient being 0.831. In the same way, there was a significant correlation between the crown diameter perpendicular to maximum diameter (b_1) and the perpendicular diameter of the accumulated sand (b_2); their correlation coefficient being 0.834. Diameters and heights of plant and accumulated sand were highly correlated with their own volumes. The correlation coefficients of crown diameters (a_1, b_1) and plant volume (V_1) were 0.824 and 0.898. The correlation coefficients of diameter of accumulated sand (a_2, b_2) and plant volume (V_1) were 0.766 and 0.706. In addition, plant volume (V_1) was highly correlated with accumulated sand volume (V_2). The correlation coefficient was 0.696.

Correlation analysis between plant volume (V_2) and accumulated sand volume (V_1) showed the optimal regression equation as $V_2 = 0.046,6\ V_1^{0.781,8}$ ($R^2 = 0.498,6$, $P < 0.01$, $n = 58$) (Fig. 3).

Table 2 Correlation matrix of the morphology variables in *S. psammophila* plants

Valuable name	Maximum crown diameter a_1	Crown diameter perpendicular to maximum diameter b_1	Plant height H_1	Maximum diameter of accumulated sand a_2	Diameter of accumulated sand perpendicular to maximum diameter b_2	Height of accumulated sand H_2	Plant volume V_1	Accumulated sand volume V_2
a_1	-	0.667**	0.643**	0.831**	0.508**	0.426**	0.824**	0.580**
b_1	-	-	0.499**	0.722**	0.834**	0.313*	0.898**	0.683**
H_1	-	-	-	0.477**	0.323*	0.100	0.706**	0.291*
a_2	-	-	-	-	0.720**	0.472**	0.766**	0.768**
B_2	-	-	-	-	-	0.369**	0.706**	0.767**
H_2	-	-	-	-	-	-	0.351**	0.742**
V_1	-	-	-	-	-	-	-	0.696**

$^{*}P < 0.01$; $^{**}P < 0.05$.

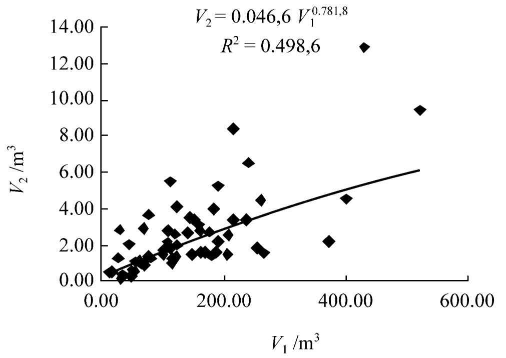

Fig. 3 Regression relationship between plant volume (V_1) and accumulated sand volume (V_2)

3.2 Characteristics of flow structure

Fig. 4 is the wind velocity profile of the anchor point in the open field, which follows an exponential law, $u^* = 0.360,4$ m/s, $z_0 = 0.500,4$ cm, $R^2 = 0.993,5$, where u^* is the frictional velocity or the shear velocity (m/s) related to the wind stress at the surface; z_0 is the surface roughness length or aerodynamic roughness length (cm). Fig. 5 shows the relative wind velocity of the various heights at the measuring points (Apr. 6). Fig. 6 shows the distribution of relative wind velocity about the single-line *S. psammophila* in the flat sands (Apr. 6). It can be seen that the relative wind velocities of the various heights at 3 *H* windward of *S. psammophila* were between 65% and 85%, increased at 2 *H* windward, then steeply decreased leeward, reached the lowest value at 1 *H* leeward, and gradually recovered to the open field velocity. The protection distance (relative wind velocity was 100%) was about 13 *H* (17 *H'*) and the effective protection distance (relative wind velocity was 80%) was about 10 *H* (13 *H'*). Single-line *S. psammophila* had a few effects on the wind velocity above plant height. When the wind velocity was at 4.00 m height, relative wind velocity decreased only to 80% at 1 *H* leeward, and it recovered rapidly to 90% at 2 *H* leeward.

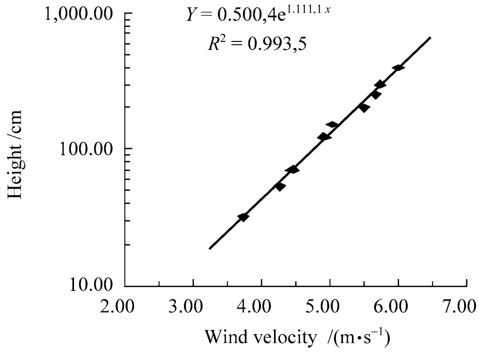

Fig. 4 Wind velocity profile of the anchor point in the open field (Apr. 6)

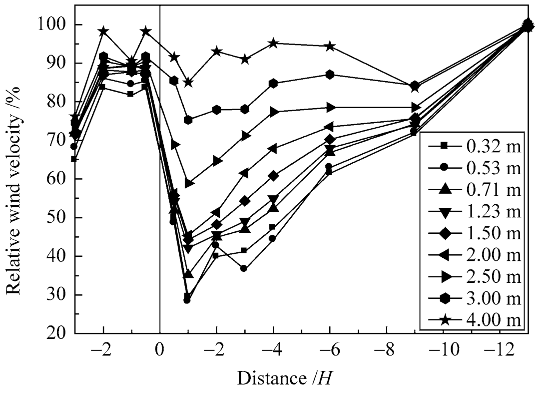

Fig. 5 Relative wind velocity of various heights at the measuring points (Apr. 6)

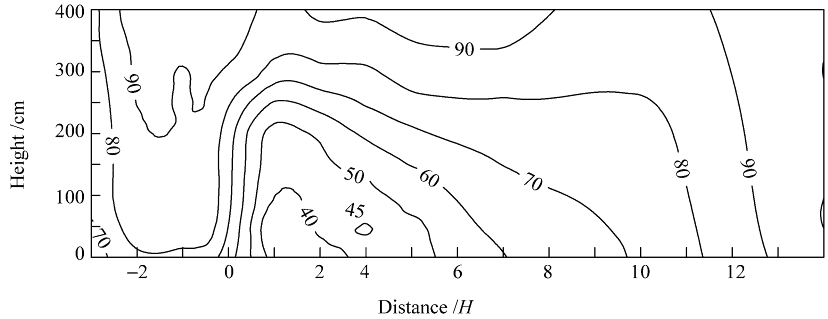

Fig. 6 Distribution of relative wind velocity (%) about the single-line *S. psammophila* in the flat sands (Apr. 6)

4 Discussions

Vertical and horizontal wind velocities greatly change close to vegetation. The perfect field investigation method is to make synchronous observations on the flat surface (He et al., 2002). However, this method is rarely adopted, since it needs many instruments. In this study, the relative wind velocity, which is the ratio of average wind velocity at any measuring point to that at the anchor point in the open field measured at the same time, was adapted to eliminate the horizontal errors derived from non-synchronous observations at various measuring points (Cao, 1983; Dong et al., 1983; Huang and Gao, 2001).

The airflow structure of vegetation was affected by many factors, which included vegetation structural features such as structural type, shelterbelt porosity, width, height, shape of cross section, and with leaf or without leaf status. Meteorological conditions, such as wind direction, wind velocity, and stratification of atmospheric temperature also affected the airflow structure, as did the surface conditions of the ground, such as surface roughness and hypsography (Cao, 1983). In this paper, airflow structure of *S. psammophila* was obtained at only this one specially combined mode of the factors mentioned. Therefore, observations at different combined modes should be further carried out for a thorough understanding of the airflow structure of *S. psammophila*.

In previous studies, a 1.7-m high reed fence with a 0.34 porous coefficient was similar to the *S. psammophila* hedge row in this study than other shelterbelts with their morphology and structure (Wang et al., 1999). Wind tunnel experiments of reed fences showed that there was a closed high velocity zone at the top lee and a closed low velocity zone at the bottom lee. The protection distance was about 20 *H*. Conformation of the low velocity zone at the bottom of the lee has been obtained, but due to the limit of our height of observation, the high velocity zone cannot be observed. For reed fences, wind velocity gradually decreased to windward along the wind direction. For sparse shelterbelts, however, it has been reported that wind velocity increased at 3–6 *H* to windward (Wu, 2003). Therefore, it was entirely conceivable that wind velocity increased at 3–4 *H′* to windward (2–3 *H*, *H* = 3.5 m, average plant height *H′* = 2.68 m). The protection distance of *S. psammophila* was about 17 *H′* and the protection effect was a little lower than that of the reed fence. In the study area, the space between the two artificially cultivated single-line *S. psammophila* was about 50 m, which was longer than the protection distance (46 m or 17 *H′*). To improve the sand-fixing and wind erosion-prevention effects of *S. psammophila*, we suggest that the spacing be set in the range of an effective protection distance (35 m or 13 *H′*).

Above all, *S. psammophila* could accumulate sand because the plant decreased the windward and leeward wind velocity. There was a significant correlation (R = 0.696) between accumulated sand volume (V_2) and plant volume (V_1), as shown by the optimal regression equation $V_2 = 0.046{,}6\ V_1^{0.781{,}8}$ ($R^2 = 0.498{,}6$, $P < 0.01$, $n = 58$). The wind velocity was 6 m/s at 4 m height of the single-line *S. psammophila* row. The wind velocity decreased at 3 *H* to windward and increased at 2 *H* to windward, then steeply decreased to leeward and reached the lowest value at 1 *H* to leeward. Finally, it gradually recovered to its open field velocity. The single-line *S. psammophila* hedge row had few effects on the wind velocity above plant height.

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