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Sand-fixing effects of *Caragana microphylla* shrub in Horqin sandy land, North China

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Abstract In the semi-arid Horqin sandy land of north China, *Caragana microphylla*, a leguminous shrub, is the dominant plant species and is widely used in vegetation reestablishment programs to stabilize shifting sand. The sand-fixing effects of 6- and 11-year-old *C. microphylla* plantations were studied. The results showed that: 1) the wind velocity and sand transport rate in the plantation were less than those in dunes; 2) the air temperature in the plantation was lower than those in dunes. Relative humidity was higher and the soil temperature was lower, which benefits plant growth; 3) the physical and chemical characteristics of soil were improved to some extent over age. The porosity and percentage of tiny sand (diameter 0.05–0.1 mm) and clay particle (diameter < 0.05 mm) increased, bulk density in surface soil decreased, and saturated water-holding capacity improved. Organic C, total N, available N and available K content increased gradually, and soil fertility was enhanced.

Keywords Horqin sandy land, *Caragana microphylla*, sand-fixing effects, sand transport rate, microclimate

1 Introduction

Horqin region, located in the northern part of China, has been one of the most severe desertification areas in the

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agro-pastoral ecotone due to fragile eco-environments and improper management of land (Wu et al., 2002; Jiang and Liu, 2003). Restoring degraded ecosystems, maintaining the stability of environments and sustainable development are important issues of modern ecology (Ma, 2002). Many measures such as planting indigenous trees, shrubs and grasses adaptive to sandy land had been implemented in restoring degraded or fragile ecosystems in China since the 1980s, and some theoretical and practical results have been achieved preliminarily. Compared with trees, shrubs have some obvious advantages: needing less water, being more suitable for poor soil moisture and nutrient conditions, and having evident sand-fixing effects. Due to its advantages of cold-tolerance, drought-tolerance, poor-soil-tolerance and heat-tolerance, *Caragana microphylla*, a leguminous shrub with thorns, is widely distributed in the Horqin sandy land and has been a favored plant in vegetation reestablishment programs. Large areas of artificial *C. microphylla* shrubs were established to stabilize drifting sand in this region in recent decades. In this paper, *C. microphylla* shrubs, cultivated on shifting sand dunes in 1995 and 2000, were selected to investigate their sand-fixing effects, and also changes of wind velocity, sand transporting rate, microclimate, physical and chemical characteristics of soil. It is expected that the results will be useful in providing theoretical basis and practical guidance for restoring vegetation in arid and semi-arid regions.

2 Study area

The study site is located at Wulan'aodu village (43°02'N, 119°39'E), Wengniute County, west of the Horqin sandy land, Inner Mongolia, China. The climate of this region is semi-arid. The average annual temperature is 6.2°C, and the non-frost period is 130 days. Annual precipitation is 340.5 mm with 70%–80% occurring during the growing season of May–September, and evaporation is 2200 mm. Average annual wind velocity is 4.5 m/s, with the frequent occurrence of gales (wind speeds ≥ 20 m/s)

in winter and spring. The landscape is characterized by gently undulating, shifting and half-shifting sand dunes with interdune depression. There are three types of soil: sandy soil, meadow soil, and saline-alkali soil. The original vegetation was the transitional type from forest to grass. However, the original vegetation has been greatly destroyed in the past several decades, and most has evolved into psammophyte and meadow vegetation (Liu and Zhao, 1996). The flora of Mongolia has the widest distribution and most species in this region.

3 Materials and methods

3.1 Materials

C. microphylla has been gradually planted on desertified lands in the experimental plots of the Wulan'aodu Experimental Station of Desertification since the early 1980s. Planting was arranged in belts (row spacing 1 m × 1 m), and the orientation of the belts was perpendicular to the prevailing wind direction. Until 2006, an age series of 6- and 11-year-old *C. microphylla* plantations were distributed on sandy land surrounding the station. The descriptions of plots are shown in Table 1.

3.2 Methods

The research items and their methods mainly included: measuring wind velocity with an AVM-03 anemometer at different heights (30, 80 and 200 cm); measuring sand transport rate at the height of 0–40 cm from the surface; analyzing the changes in physical and chemical characteristics of soil at different depths (soil samples were collected from three random locations within each plot in April 2006) (ISSCAS, 1978). To find the relationship between microclimate and reestablishment of degraded vegetation, microclimate characteristics within each plot were investigated in June 2006, including air temperature and relative humidity (using a wet-and-dry bulb thermometer, which has been corrected by an Assmann psychrometer) at different heights (0 and 30 cm), and soil temperature at three depths (0, 5, and 10 cm). All statistical analyses were performed using the Microsoft Excel and SPSS11.5 software packages.

4 Results and analysis

4.1 Wind-breaking and sand-fixing effects of *C. microphylla* shrubs

4.1.1 Wind-breaking effects

The wind velocity at each height of shifting dunes was set as 100% (Fig. 1). With the height decreasing, the wind-breaking effects of *C. microphylla* shrubs became more and more significant. Compared with shifting dunes, wind velocity passing through the 6- and 11-year-old *C. microphylla* shrubs at the height of 200, 80 and 30 cm decreased by 17.94%, 31.59%, 71.86% and 27.94%, 39.72%, 75.96%, respectively. These results indicated that vegetation cover had an obvious blocking effect on wind velocity near ground surface, and the effect was better for the 11-year-old shrubs.

4.1.2 Characteristics of wind-sand current structure

Fig. 2 shows the characteristics of wind-sand current structure at the height of 0–40 cm within different plots.

Under the same wind velocity conditions, there was a significant difference in total and individual layer sand transport rates within different plots. The rates in the shifting dunes were faster than those in the 6- and 11-year-old *C. microphylla* shrubs; the 6-year-old shrubs had faster rates than 11-year-old shrubs. In the shifting dunes, the total sand transport rate in 6- and 11-year-old *C. microphylla* shrubs were 132.04, 2.22 and 1.15 g/(cm·h), respectively. The results showed that vegetation cover was an effective measure in controlling wind erosion.

The individual layer sand transport rate in the shifting sand dunes, 6- and 11-year-old *C. microphylla* shrubs were reduced sharply with an increase in vertical height. The relationship between sand transport rate (y , g/(cm·h)) and vertical height (x , cm) could be described by a negative exponential distribution ($y = ae^{-bx}$, where a and b are regression coefficients), and the correlation coefficients were 0.9932, 0.9331 and 0.9767, respectively.

4.2 Microclimate effects of *C. microphylla* shrubs

The development of shrubs can change soil and air temperature and the moisture condition of surface soil,

Table 1 The habitats of plots

| plot | total coverage of vegetation | density of <i>C. microphylla</i> /trees·hm ⁻² | mean height and crown size of <i>C. microphylla</i> /cm | | main plant species |
|-----------------------------------|------------------------------|--|---|----------|--|
| Shifting dunes | < 5% | 0 | 0 | 0 | <i>Artemisia wudanica</i> , <i>Agriophyllum arenarium</i> |
| 6-year-old <i>C. microphylla</i> | 50% | 6438 | 81 | 99 × 82 | <i>Artemisia halodendron</i> , <i>Corispermum candelabrum</i> , <i>Setaria viridis</i> , <i>Cynanachum sibiricum</i> |
| 11-year-old <i>C. microphylla</i> | 70% | 7625 | 97 | 106 × 96 | <i>A. halodendron</i> , <i>C. candelabrum</i> , <i>S. viridis</i> , <i>C. sibiricum</i> , <i>Salsola ruhtenica</i> |

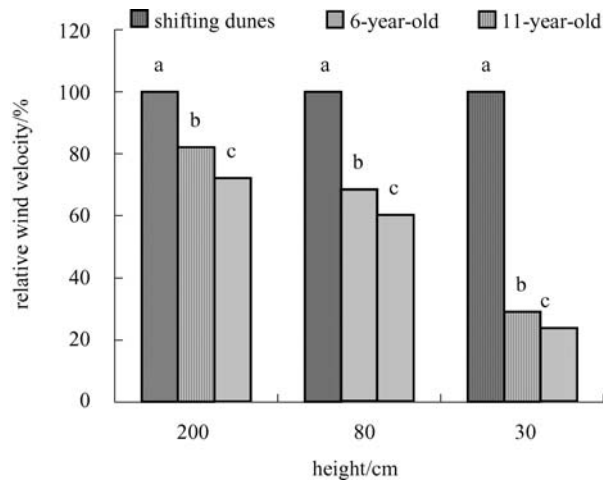


Fig. 1 Wind-breaking effect of *C. microphylla* shrubs. The different letters within a category are significantly different ($P < 0.05$).

and then improve the microclimate, creating a favorable surrounding for plant growth (Holmgren and Scheffer, 2001). After shifting dunes are fixed by *C. microphylla*, damage from sand blown by the wind is alleviated and the environment is improved.

4.2.1 Influence on air temperature

Air temperature at different heights showed that daily temperature within all of the three plots took on the same trend. Mean daily temperature in shifting dunes at the height of 0 and 30 cm was 4.47°C and 2.97°C higher than that in the 6-year-old *C. microphylla* shrub, and 5.90°C and 3.90°C higher than that in the 11-year-old *C. microphylla* shrub, respectively. Therefore, *C. microphylla* shrubs can decrease air temperature in the sand in summer (Table 2).

4.2.2 Influence on relative humidity

Air relative humidity is a synthetic reflection of microclimate. The diurnal variation of air relative humidity within the three plots were approximately the same (Table 2), and the air relative humidity in the 6- and 11-year-old *C. microphylla* shrubs was higher than that in shifting dunes at any time, especially at 8:00 and 20:00. Mean diurnal relative humidity in the 6- and 11-year-old shrubs was 13.7% and 21.2% higher than that in shifting dunes, respectively. The results showed that vegetation coverage evidently increases humidity.

4.2.3 Influence on soil temperature

Temperature in shallow-layer soil of vegetation areas was different from shifting sand dunes (Table 2). At each depth, the maximum soil temperature (14:00) of the *C. microphylla* shrubs was lower than that of the shifting dunes, while the minimum shrub temperature (8:00) was a little higher than that for dunes. In summary, the daily soil temperature

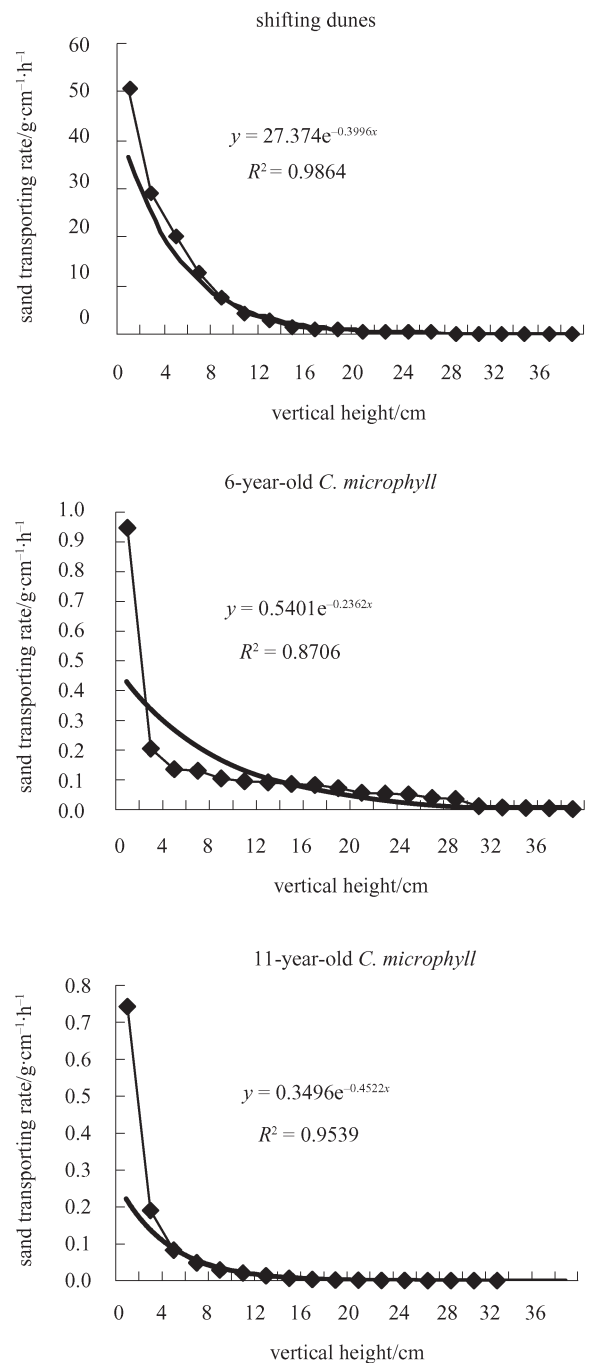


Fig. 2 Characteristics of wind-sand current structure in different plots.

ranges for the 6- and 11-year-old shrubs were smaller than that for shifting dunes, and the soil temperature varied mitigatively, which was beneficial to the growth of plants.

4.3 Changes in physical and chemical properties of soil

4.3.1 Changes in mechanical composition and physical properties of soil

After establishing vegetation on the shifting sand dunes, the physical and chemical properties of soil changed

Table 2 Microclimate measurement of shifting dunes and *C. microphylla* shrubs in June

| plot | time | air temperature/°C | | air relative humidity/% | | soil temperature/°C | | |
|-----------------------------------|-------|--------------------|-------|-------------------------|-------|---------------------|------|-------|
| | | 0 cm | 30 cm | 0 cm | 30 cm | 0 cm | 5 cm | 10 cm |
| Shifting dunes | 8:00 | 33.1 | 29.8 | 24 | 25 | 27.5 | 19.1 | 19.0 |
| | 14:00 | 39.8 | 38.0 | 20 | 15 | 43.2 | 33.0 | 31.2 |
| | 20:00 | 28.1 | 27.9 | 29 | 26 | 30.1 | 30.8 | 29.0 |
| 6-year-old <i>C. microphylla</i> | 8:00 | 26.2 | 27.6 | 42 | 43 | 21.8 | 20.2 | 19.7 |
| | 14:00 | 35.6 | 33.9 | 29 | 26 | 41.6 | 32.8 | 29.4 |
| | 20:00 | 25.8 | 25.3 | 43 | 38 | 28.7 | 28.8 | 28.2 |
| 11-year-old <i>C. microphylla</i> | 8:00 | 22.9 | 25.7 | 55 | 51 | 21.3 | 20.0 | 19.5 |
| | 14:00 | 34.7 | 35.5 | 35 | 29 | 36.5 | 28.4 | 26.7 |
| | 20:00 | 25.7 | 22.8 | 42 | 54 | 27.3 | 27.3 | 27.0 |

gradually due to the influence of plant roots, soil microbes and animals.

With the fixation of shifting dunes, mechanical composition of soil changed with a decrease in wind velocity and the deposition of erodible soil particles. Over the age of a plantation, the percentage of moderate sand (diameter 0.25–1 mm) and fine sand (diameter 0.1–0.25 mm) in the surface layer (0–5 cm) decreased gradually, while the percentage of tiny sand (diameter 0.05–0.1 mm) and clay particles (diameter < 0.05 mm) had a reverse trend, which indicated that the change of mechanical composition was relative to the accumulation of aeolian deposits when wind velocity decreased in the shrubs.

As shown in Table 3, soil bulk density decreased gradually over age, while soil capillary porosity increased with an increase in depth. With the development of artificial vegetation, noncapillary porosity and total porosity increased, while capillary porosity decreased. Soil thus had a stronger ability to absorb and reserve water with a decrease in soil bulk density and an increase in porosity, which has ecological significance in arid desert regions.

4.3.2 Changes in chemical properties of soil

Restoring a degraded ecosystem should restore its vegetation firstly, and then soil texture and nutrient conditions will be improved with interaction between plant and soil.

In the process of restoring vegetation, the soil pH decreased slightly, especially in the surface layer (0–10 cm)

(Table 4). This was probably due to the accumulation of humic acid in the soil with restoration, and organic acid in the soil increased with enhanced microbe activity. The changes to soil nutrients resulted from the interaction between large geo-cycling and small bio-cycling, and animals played a crucial role in the soil-forming process of parent material. After vegetation establishment on the shifting sand dunes, organic C, total N, available N and available K content obviously increased, while total P and available P content decreased. *C. microphylla* shrubs thus promoted nutrient cycling and accumulation of soil material, the nutrient content increased gradually, and soil fertility was enhanced.

5 Discussion and conclusions

C. microphylla shrubs had an obvious blocking effect on wind velocity near the ground surface. Compared with shifting dunes, the wind velocity in the 6- and 11-year-old *C. microphylla* shrubs decreased by 71.86% and 75.96% respectively at the height of 30 cm. The total and individual layer sand transport rates in *C. microphylla* shrubs were lower than those in dunes. The total sand transport rate in dunes was 132.04 g/(cm·h), which was 59.5-fold and 115.8-fold that in the 6- and 11-year-old shrubs, respectively. The sand transport rate of each layer within the three plots decreased sharply with increasing vertical height, and the relationship between sand transport rate (y , g/(cm·h)) and height (x , cm) could be

Table 3 Changes in physical properties of soil at different depths

| plot | depth/cm | soil bulk density/g·cm ⁻³ | soil noncapillary porosity/% | soil capillary porosity/% | total soil porosity/% |
|-----------------------------------|----------|--------------------------------------|------------------------------|---------------------------|-----------------------|
| Shifting dunes | 0–10 | 1.66 | 5.43 | 33.95 | 39.38 |
| | 10–20 | 1.69 | 5.18 | 34.41 | 39.59 |
| | 20–30 | 1.68 | 4.66 | 35.27 | 39.93 |
| 6-year-old <i>C. microphylla</i> | 0–10 | 1.59 | 7.57 | 34.70 | 42.27 |
| | 10–20 | 1.63 | 7.96 | 33.98 | 41.94 |
| | 20–30 | 1.64 | 7.88 | 33.58 | 41.46 |
| 11-year-old <i>C. microphylla</i> | 0–10 | 1.57 | 8.57 | 33.80 | 42.37 |
| | 10–20 | 1.61 | 6.74 | 33.94 | 40.68 |
| | 20–30 | 1.63 | 4.96 | 35.01 | 39.97 |

Table 4 Changes to chemical properties of soil at different depths

| plot | depth/cm | pH | total organic C/g·kg ⁻¹ | total N/g·kg ⁻¹ | total P/g·kg ⁻¹ | alkaline N/mg·kg ⁻¹ | available P/mg·kg ⁻¹ | available K/mg·kg ⁻¹ |
|--------------------------------------|----------|------|---------------------------------------|-------------------------------|-------------------------------|-----------------------------------|------------------------------------|------------------------------------|
| Shifting dunes | 0–10 | 7.18 | 1.33 | 0.29 | 0.0556 | 4.48 | 5.07 | 46.60 |
| | 10–20 | 7.07 | 0.94 | 0.17 | 0.0557 | 5.23 | 3.97 | 41.94 |
| | 20–30 | 7.08 | 1.01 | 0.19 | 0.0489 | 2.99 | 4.70 | 46.80 |
| 6-year-old <i>C. microphylla</i> | 0–10 | 7.14 | 1.23 | 0.41 | 0.0623 | 10.16 | 3.35 | 70.87 |
| | 10–20 | 7.08 | 1.20 | 0.28 | 0.0491 | 7.13 | 2.70 | 41.60 |
| | 20–30 | 7.07 | 1.14 | 0.25 | 0.0481 | 6.14 | 2.95 | 35.20 |
| 11-year-old <i>C. microphylla</i> | 0–10 | 7.09 | 1.29 | 0.62 | 0.0556 | 11.90 | 3.97 | 87.53 |
| | 10–20 | 7.07 | 1.32 | 0.33 | 0.0445 | 8.46 | 2.47 | 52.84 |
| | 20–30 | 7.04 | 1.31 | 0.30 | 0.0389 | 7.26 | 2.43 | 36.68 |

described by a negative exponential distribution ($y = ae^{bx}$, where a and b are regression coefficients), which had been proven by wind tunnel simulation and field investigation (Chepil, 1945; Zou et al., 1992; Zhang et al., 2002).

The microclimate, the result of interaction between vegetation and environment, is a synthetic reflection of community quality and an important criterion of vegetation restoration (Li et al., 2005). After establishing *C. microphylla* shrubs as sand binders, the air temperature in the plantation was lower than that in shifting dunes, the relative humidity was higher, and the daily soil temperature range was smaller. Obviously, microclimate in the shrubs improved significantly, which benefits plant habitation and growth.

Sand-fixation by vegetation not only protected shifting sand dunes, but also promoted the evolution from sand to soil. The restoration of vegetation and soil interacted each other, and the interaction function was enhanced over the plantation's age. The physical and chemical properties of soil were improved to some extent after establishing vegetation. Over time, soil porosity increased, mechanical composition and bulk density in surface soil decreased, and saturated water-holding capacity improved. Organic C, total N, available N and available K content increased gradually, and soil fertility was enhanced. However, total P and available P content decreased, contrasting the study of Cao (2004). This could be due to the shorter planting age of *C. microphylla* shrubs selected in this paper and the absorption and storage of P in the plants, which resulted in the decrease of P in the soil. Over time, P would return to soil through litter decomposition, which was proven by the analysis of physical and chemical properties of soil in the 22-year-old *C. microphylla* shrub. The content of total P and available P at the depth of 0–10 cm, 10–20 cm and 20–30 cm in the 22-year-old shrub were 0.0986, 0.0523, 0.0460 g/kg, 7.21, 3.74 and 2.64 mg/kg, respectively. The results showed the content of P began to increase, especially in the surface layer.

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