available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/ecoleng

Shrub facilitation of desert land restoration in the Horqin Sand Land of Inner Mongolia

Ha-Lin Zhao[a,*], *Rui-Lian Zhou*[b], *Yong-Zhong Su*[a], *Hua Zhang*[a], *Li-Ya Zhao*[a], *Sam Drake*[c]

[a] *Cold and Arid Regions Environment and Engineering Institute, Lanzhou 730000, China*
[b] *Faculty of Life Sciences, Eastern Shandong University, Yantai 264025, China*
[c] *Office of Arid Lands Studies, University of Arizona, 1955 E. 6th Street, Tucson, AZ 85719, USA*

ARTICLE INFO

Article history:
Received 22 July 2006
Received in revised form
9 March 2007
Accepted 15 April 2007

Keywords:
Shrub effects
Soil properties
Seed bank
Desertification
Restoration
Inner Mongolia

ABSTRACT

To understand the status and roles of shrubs in recovery processes of desertified land in the semi-arid areas of China, we investigated the effects of shrub canopy on soil properties, organic litter, seed bank and understory herbaceous community properties in the Horqin Sand Land, Mongolia. The results showed that in shifting sand dunes, content of very fine sand, silt and clay, organic matter, total N and P, available P and soil moisture at 0–20 cm depth was higher under remnant shrub canopies of *Caragana microphylla* and *Salix gordejevii* than in open space. Soil seed density was nearly 12 times higher under *Artemisia halodendron* canopy than in open space. The herbaceous perennial *Pennisetum centrasiaticum*, usually restricted to fixed sand dunes, not only survived under shrub canopy in shifting sand dunes, but also had higher plant densities, plant height, cover and aboveground biomass. After fencing shifting sand dunes and establishing shrub plantings, fine soil particles, soil nutrients, plant species richness, vegetation cover and aboveground biomass increased gradually both under shrub canopy and in open spaces with increasing enclosure or plantation age, but the speed of restoration processes was significantly higher under canopy compared to open spaces. These results suggest that shrubs created significant "islands of fertility" and had an important role in maintaining or augmenting herbaceous species richness in shifting sand dunes, and could improve soil properties and facilitate vegetation recovery for controlling desertification processes.

1. Introduction

Desertification is one of the main types of land degradation in arid and semi-arid areas. In particular, desertification of sandy areas driven by wind erosion often results in coarse, poor soil and low land productivity, which can degrade the human living environment and impede socioeconomic development. Thus in recent years, the study and control of sandy area desertification are receiving increased attention by the international community (Su et al., 2002; Zhao et al., 2004).

Shrubland or shrub-hummock is one of the main vegetation types commonly found in arid and semi-arid areas (Facelli and Temby, 2000). Some shrub species in these areas have greater drought hardiness and wind erosion resistance, and a few species are adapted to partial sand burial (Li et al., 1992), some shrub species are thus retained during desertification processes, even on shifting sand lands (Su et al., 2002; Li et al.,

* *Corresponding author*. Tel.: +86 931 4967860; fax: +86 931 4967201.
E-mail address: zhaohalin666@hotmail.com (H.-L. Zhao).
0925-8574/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecoleng.2007.04.010

2003). Such hardy shrub species are often used to construct plantations for controlling land desertification (Su et al., 2002; Zhao et al., 2004).

There is a great body of literature on shrub effects in grassland or desert ecosystems, including studies of shrub spatial aggregation and its consequences (Belsky and Canham, 1994), effects of shrubs on soil characteristics and annual-plant communities (Facelli and Temby, 2000; Wezel et al., 2002), seed bank and understory species composition (Pugnaire and Lázaro, 2000), mechanisms of interaction between shrubs and understory layers (Moro et al., 1997), and so on. Many results show that in arid and semi-arid systems, herbaceous plants are more abundant (Maestre and Cortina, 2002), and soil and microclimatic conditions are improved beneath the canopies of shrubs compared with open spaces (Titus et al., 2002). Characteristics of shrub patches such as species identity, age and size strongly influence seed banks, seedling recruitment, community composition and succession processes of understory species (Facelli and Temby, 2000; Maestre and Cortina, 2005) and strongly influence community structure and dynamics in semi-arid ecosystems (Pugnaire and Lázaro, 2000). According to the theory of island biogeography of MacArthur and Wilson (1967), these shrub or hummock patches may be treated as “islands” of woody vegetation within a sea of grassland or desert vegetation, and may act as “resource islands” for understory herbaceous plants in recovery processes of degraded vegetation (Reynolds et al., 1999; Maestre and Cortina, 2005).

Horqin Sand Land, located in the northeastern part of China (42°41′-45°15′N, 118°35′-123°30′E), is one of the areas of most serious concern for land desertification in China, where desertified land comprises 57.8% of the total area (Zhao et al., 2004). However, since the mid-1970s some successful measures to combat desertification have been implemented, such as planting indigenous trees, shrubs and grasses adapted to sandy land, fencing grassland against grazing and using minimum tillage (Su et al., 2002). These have decreased the desertified area from 5163 km^2 in 1987 to 4674 km^2 in 2000 (Zhao et al., 2005). To understand the mechanisms of restoration of desertified lands, researchers have investigated the effects of several shrubs on soil chemical properties (Su et al., 2002), changes in soil properties after afforestation (Shirato et al., 2004) and effects of grassland enclosure on soil seed bank and plant community structure in these areas (Li et al., 2003). The main objectives of this study were: (1) to compare several biotic and abiotic variables in the bare soil or open spaces between shrubs versus under shrub canopies, including herbaceous biomass, seed bank patterns and soil physical and chemical properties; (2) to investigate changes in soil properties and plant species composition in an age-sequence of shrub plantations; (3) to evaluate the facilitative effects of shrubs on restoration of desertified land.

2. Materials and methods

2.1. Study area

The study area is located at Yaoledianzi village (42°55′N, 120°41′E, elevation 345 m), Naiman county, in the southwestern end of Horqin Sandy Land, Inner Mongolia, China, and

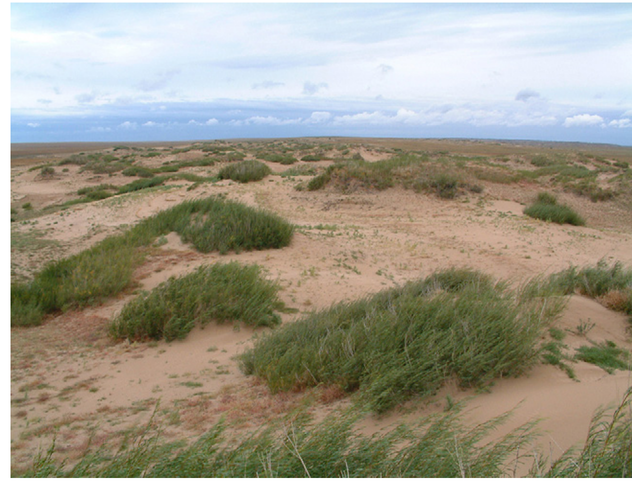

Fig. 1 – Shifting sand dunes typical of the study area.

belongs to a monitoring area of the Naiman Desertification Research Station (NDRS), Chinese Ecosystem Research Network. The climate of this region is a temperate continental semi-arid monsoon regime. The annual mean precipitation is 366 mm, annual mean potential evaporation is 1935 mm and annual mean temperature is 6.8 °C. The average annual wind velocity is 3.4 $m\,s^{-1}$, with mean spring-season wind speed of 4.3 $m\,s^{-1}$. The landscape is characterized by gently undulating, shifting and semi-shifting dunes and fixed dunes, as shown in Figs. 1 and 2. The vegetation consists largely of low, open shrubland dominated by *Caragana microphylla*, *Salix gordejevii* and *Artemisia halodendron*, with a herbaceous stratum dominated by *Pennisetum centrasiaticum*, *Corispermum macrocarpum* and *Setaria viridis* (Zhao et al., 2005).

2.2. Soil and vegetation properties in open spaces and under shrub canopies

Two sites were selected on shifting sand dunes. One, with remnant shrubs *C. microphylla* and *S. gordejevii*, was fenced at the end of 1990 to protect it from grazing by livestock.

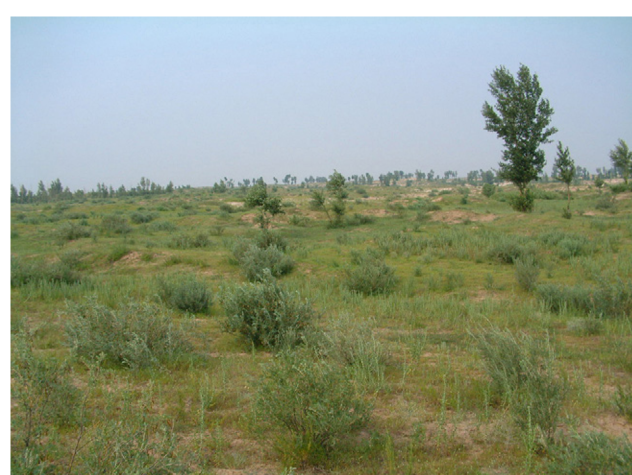

Fig. 2 – Fixed sand dunes in study area.

Soil samples were collected at 0–5 cm depth, and herbaceous community properties were investigated under three *C. microphylla* and three *S. gordejevii* shrubs and in associated open spaces at this site in early September of 1990, 1996 and 2003. At the second site, *C. microphylla* plantations were established 5, 13 and 21 years ago on land with similar soil properties. Within each plantation (5, 13 and 21 years) and in an adjacent site of shifting sand dunes with no plantation (“age 0”, Tables 4 and 5), three shrubs and associated open spaces were selected for sampling (three replicates). Soil samples were collected at 0–5 cm depth, and herbaceous community properties were investigated in early 2002. Each soil sample was obtained by mixing five sub-samples collected from beneath each plant and from each open space. Samples were placed in sealed plastic bags and sent to the NDRS laboratory. Herbaceous vegetation properties including plant species present, plant density, plant height, percent cover and aboveground biomass were measured in four replicate quadrats, each 20 cm × 20 cm.

2.3. *Seed bank analyses in open spaces and under shrub canopies*

We assessed the viable soil seed bank (i.e., the seeds that readily germinate under favorable moisture conditions) under individuals of *A. halodendron* and in open spaces. This measure provides estimates of the potential plant community, but it is not a complete assessment of the seed populations, because seeds of some species may not germinate, or the germination fractions of the various species may be different (Simpson et al., 1989). Soil samples were collected from the study area in March 2002, before any spring germination occurred. We chose five *A. halodendron* plants with approximately 100 cm height and 150 cm canopy diameter in the shifting sand dune area. From open spaces outside each shrub and from beneath each shrub canopy we collected the soil from nine regularly spaced quadrats (20 cm × 20 cm × 5 cm) at four different aspects (NE, NW, SW and SE). In the laboratory, the soil from each sample was thoroughly sieved to 4 mm to remove organic litter, and then the soil was placed into plastic trays in the greenhouse. The trays were watered at least three times a week, or as needed, to keep the soil moist without waterlogging it. Seedlings were identified and counted weekly until emergence ceased. Once a seedling was identified, it was removed to minimize possible density-dependent effects on further germination (Facelli and Temby, 2000).

2.4. *Soil sample and data analyses*

In the laboratory, each soil sample was thoroughly sieved to 2 mm to remove roots and incorporated litter. Part of each sieved sample was air-dried for determining particle size distribution and selected chemical properties. Soil particle size distribution was determined by the pipette method in a sedimentation cylinder, using Na-hexamethaphosphate as the dispersing agent (Day, 1965). Soil pH and electrolytic conductivity were determined with a combination pH electrode (Multiline F/SET-3, Germany) in a 1:1 soil–water slurry and 1:5 soil–water aqueous extract, respectively. Soil organic matter was measured by the $K_2Cr_2O_7$–H_2SO_4 oxidation method (ISSCAS, 1978), total N by the Kjeldahl procedure (UDK 140 Automatic Steam Distilling Unit, Automatic Titroline 96, Italy) (ISSCAS, 1978) and total P by UV-1601 Spectrophotometer (Japan), after H_2SO_4–$HClO_4$ digestion (ISSCAS, 1978). Soil available N was determined by the alkalisable diffusion method, and available P determined by the Bray method (ISSCAS, 1978).

All data were analyzed using the SPSS program for Windows Version 11.5 (Su et al., 2002). Multiple-comparison and one-way analysis of variance (ANOVA) procedures were used to compare the differences among the treatments (Sokal and Rohlf, 1995). Least significant difference (LSD) tests were performed to determine the significance of treatment means at $P < 0.05$.

3. Results

3.1. *Soil properties in open spaces and beneath shrub canopies*

Independent of shrub species, most of the analyzed soil parameters showed that differences exist between the soils under shrubs and those in the nearby open spaces (Table 1). Generally, coarse sand content, fine sand content, bulk density and available N were lower, while very fine sand content, clay + silt content, soil moisture, organic matter, total N and P and available P were higher under the canopies than in the open spaces. However, different shrub species influenced soil parameters to different degrees. The enrichment ratios of organic matter and total N and P were significantly greater for *C. microphylla* compared with *S. gordejevii*, and the enrichment ratios of available N and P were somewhat greater for the former compared to the latter, but the enrichment ratio of silt + clay was similar between the two.

3.2. *Soil seed bank in open spaces and beneath shrub canopies*

Overall, the viable soil seed bank under shrubs was significantly richer than in open spaces ($P < 0.05$) (Table 2). Average seed density was 598 seeds/m^2 under the shrubs, and 50 seeds/m^2 in the open spaces nearby, a 12-fold difference. There was a significant decreasing trend in soil seed density from the center of the shrub canopy to the open space outside the shrub canopy ($P < 0.05$). The seed quantity decreased rapidly from 918 seeds/m^2 in the center to 277 seeds/m^2 at the margin of the shrub canopy, to only a few seeds at 4–5 m distance from the shrub canopy. Soil seed distribution showed great differences at different orientations under and outside the shrub canopy. Beneath the shrub canopy, average seed density was highest in the southwest (1135 seeds/m^2), and least in the northeast (186 seeds/m^2). In open space outside the canopy, seed density was highest in the southeast (109 seeds/m^2), and least in the northwest (7 seeds/m^2). This distribution may be related to the prevailing north and northwest winds (Zhao et al., 2004).

Table 1 – Soil properties in open spaces and under remnant shrub canopies on shifting sand dunes

Items	Shrub species	*Caragana microphylla*		*Salix gordejevii*	
	Position	Canopy	Open	Canopy	Open
Soil particle size distribution (%)	Coarse sand	0.18 ± 0.06	0.60 ± 0.19	0.23 ± 0.03	0.42 ± 0.03
	Fine sand	7.78 ± 1.05	20.96 ± 1.42a	17.24 ± 1.23	21.78 ± 1.33a
	Very fine sand	83.35 ± 2.74	71.03 ± 1.18a	73.75 ± 0.43	71.29 ± 2.05a
	Silt + clay	8.63 ± 1.09	7.41 ± 1.04	7.66 ± 0.50	6.51 ± 0.16
	Enrichment ratio	1.16		1.17	
Soil bulk density (g/cm^3)		1.56 ± 0.10a	1.64 ± 0.02a	1.63 ± 0.01a	1.65 ± 0.02
Soil moisture(%)		4.01 ± 1.70a	3.62 ± 0.60a	1.55 ± 0.11	1.21 ± 0.10
OM (%)	Values	0.23 ± 0.05	0.16 ± 0.04	0.12 ± 0.02	0.10 ± 0.02
	Enrichment ratio	1.44		1.20	
Total N (g/kg)	Values	0.14 ± 0.03	0.10 ± 0.02	0.07 ± 0.02	0.06 ± 0.02
	Enrichment ratio	1.40		1.17	
Total P (g/kg)	Values	0.16 ± 0.02	0.13 ± 0.02a	0.13 ± 0.01a	0.12 ± 0.01a
	Enrichment ratio	1.23		1.08	
Available N (mg/kg)	Values	25.52 ± 5.26a	26.82 ± 7.62a	18.09 ± 5.16b	21.73 ± 5.01b
	Enrichment ratio	0.95		0.83	
Available P (mg/kg)	Values	9.01 ± 1.60	7.75 ± 2.00	3.34 ± 1.27a	3.02 ± 1.23a
	Enrichment ratio	1.16		1.11	

Values are means ± S.D. Values with the same letters within rows are not significantly different at $P < 0.05$.

3.3. *Herbaceous vegetation change under shrub canopies*

Shrubs had significant effects on the herbaceous community under the canopy (Table 3). Although there were no herbaceous plants in open lands outside shrub canopies on the shifting sand dunes (year 0), the herbaceous perennial *P. centrasiaticum* survived under *C. microphylla* canopy. Plant density, height, cover and aboveground biomass for *P. centrasiaticum* reached up to 107 plants/m^2, 42.0 cm, 41.0% and 219 g/m^2, respectively, under the canopy, but they disappeared quickly at the shrub margins.

Changes occurred in herbaceous community properties under *C. microphylla* canopy after grazing disturbance was removed. With increasing enclosure age, the herbaceous cover expanded and certain community properties improved significantly ($P < 0.05$). In comparison with shifting sand dunes (age 0), average species number, plant density, cover and aboveground herbaceous biomass under shrub canopies increased by 350.0, 142.1, 39.0 and 12.3% in the 6-year-old enclosure, and by 770.0, 230.8, 87.8 and 23.7% in the 13-year-old enclosure, respectively. The average herbaceous patch diameter increased from 3.0 m (0-year) to 19.0 m (6-year), to more than 22 m (13-year).

3.4. *Change processes of soil properties in shrub plantations*

There were clear trends of change in soil physical and chemical properties along the time gradient of the 0–21-year-old plantations (Table 4). At 0–5 cm depth, sand content and bulk density decreased from 97.3% and 1.70 g/cm^3 in the non-vegetated sandy soil (0-year) to 85.6% and 1.38 g/cm^3 under shrub canopy, and to 87.4% and 1.48 g/cm^3 in the interspaces

Table 2 – Viable seed bank densities in open space and under *Artemisia halodendron* canopy in shifting sand dunes, at varying distances from center of shrub canopy in four aspect directions

Position	Distance from center of shrub (m)	NE	NW	SE	SW	Average
Under shrub canopies	0	275 ± 71	503 ± 150	1125 ± 276	1768 ± 505	918 ± 671a
	0.25	216 ± 51	377 ± 112	878 ± 188	1346 ± 376	704 ± 512a
	0.50	156 ± 33	251 ± 75	631 ± 99	924 ± 247	491 ± 355
	0.75	97 ± 21	126 ± 37	384 ± 21	502 ± 118	277 ± 198
	Average	186 ± 77	314 ± 162	755 ± 319	1135 ± 545	597 ± 276
In open space	1	38 ± 25	18 ± 5.0	138 ± 83a	40 ± 7	59 ± 54b
	2	23 ± 11a	9 ± 35a	154 ± 31a	8 ± 5	49 ± 71b
	3	18 ± 5a	9 ± 3a	170 ± 59	4 ± 3	50 ± 80b
	4	13 ± 0a	0 ± 0a	85 ± 29	0 ± 0a	25 ± 41
	6	8 ± 5a	0 ± 0a	0 ± 0	0 ± 0a	2 ± 4
	Average	20 ± 12	7 ± 8	109 ± 69	10 ± 17	50 ± 30

Values are means (seeds/m^2) ± S.D. Values with the same letters within columns are not significantly different at $P < 0.05$.

Table 3 – Changes in herbaceous plant community properties in open space and under *Caragana microphylla* shrub canopy in a time series of vegetation restoration after fencing to exclude grazing

Items	Restoration period (years)	Beneath canopies	Open space, distance from canopy center (m)				
			0.5	2	4	6	8
Species number	0	1.0 ± 0.0	1.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0a
	6	4.5 ± 0.8	4.6 ± 0.5	4.7 ± 0.3	2.0 ± 0.0	2.0 ± 0.0	0.0 ± 0.0a
	13	8.7 ± 0.4	7.5 ± 0.6	8.3 ± 0.0	4.5 ± 0.6	4.2 ± 0.5	3.7 ± 0.2
Density (plants/m^2)	0	107 ± 9	22 ± 7	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	6	259 ± 32	189 ± 21	109 ± 11	97 ± 20	65 ± 11	23 ± 8
	13	354 ± 28	325 ± 53	339 ± 10	208 ± 31	135 ± 22	115 ± 19
Height (cm)	0	42 ± 3.2a	26 ± 1.4	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	6	42 ± 3.7a	30 ± 5.0	25 ± 3.4	19 ± 1.4	14 ± 3.2a	12 ± 2.3b
	13	42 ± 2.5a	40 ± 3.1	41 ± 3.2	29 ± 3.3	13 ± 3.5a	13 ± 4.5b
Cover (%)	0	41 ± 4.2	16 ± 1.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	6	57 ± 3.1	45 ± 3.0	17 ± 2.1	14 ± 2.5	6 ± 2.3	7 ± 3.5
	13	77 ± 4.5	74 ± 4.3	72 ± 4.2	47 ± 6.3	31 ± 11	31 ± 9.0
Biomass (g/m^2)	0	219 ± 10	87 ± 2	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	6	246 ± 18	167 ± 20	110 ± 11	49 ± 19	38 ± 10	28 ± 8
	13	271 ± 27	278 ± 24	254 ± 31	149 ± 28	105 ± 47	80 ± 10

Values are means ± S.D. Values with the same letters within columns are not significantly different at $P < 0.05$.

of the 21-year-old plantation site. In the same period, silt, clay and soil water holding capacity (WHC) increased from 2.0, 0.6 and 20.5% in the non-vegetated sandy soil to 11.1, 3.3 and 28.8% under shrub canopies, and 10.5, 2.1 and 23.0% in the interspaces, respectively. The establishment and development of shrub plantations also resulted in an enrichment of soil organic C and total N. Carbon and total N buildup at the 0–5 cm depth increased by 15.8 and 1.9 times under the shrub canopies, and 4.9 and 6.6 times in the interspaces, respectively, from the non-vegetated sandy soil after 21 years of shrub occupancy. The C:N ratio in non-vegetated dunes was lowest, and the ratio increased gradually and became nearly constant at 21 years after shrub establishment. Soil pH declined and the EC increased significantly with shrub development ($P < 0.05$). During 21 years of shrub growth, soil pH was reduced from 7.80 to 7.65 under shrub canopies and from 7.80 to 7.52 in the interspaces, while EC increased from 18 to 100 μs/cm under shrub canopies, and from 18 to 70 μs/cm in the interspaces.

3.5. *Development of herbaceous vegetation in shrub plantations*

A herbaceous plant community developed gradually in *C. microphylla* plantations, increasing in species richness, plant density and cover with increasing plantation age (Table 5). Initially (0–5 years), the herbaceous community developed

Table 4 – Soil physical and chemical properties in 0–5 cm depth under canopies and in open spaces in *Caragana microphylla* plantations of different establishment age

Items	Sampling location	Plantation age (years)				Items	Sampling location	Plantation age (years)			
		0	5	13	21			0	5	13	21
Sand (%)	Canopy	97.3	93.7	87.8	85.6	Organic C (g/kg)	Canopy	0.28	1.30	3.78	4.69
	Open	97.3	93.4	89.7	87.4		Open	0.28	0.54	2.31	3.16
Silt (%)	Canopy	2.0	4.6	8.3	11.1	Total N (g/kg)	Canopy	0.062	0.238	0.616	0.682
	Open	2.0	4.6	7.9	10.5		Open	0.062	0.185	0.385	0.469
Clay (%)	Canopy	0.6a	1.7ab	3.9c	3.3bc	C/N ratio	Canopy	4.62	5.55	6.30	7.44
	Open	0.6	2.0a	2.5	2.1a		Open	4.62a	4.44a	6.16	6.98
BD[a] (g/m^3)	Canopy	1.70	1.54	1.45	1.38	pH (H_2O)	Canopy	7.79a	7.84a	7.62b	7.65b
	Open	1.70	1.57a	1.51ab	1.48b		Open	7.79	7.69a	7.66a	7.52
WHC[b] (%)	Canopy	20.5a	23.0a	26.8b	28.8b	EC[c] (μs/cm)	Canopy	18	66a	78a	100
	Open	20.5a	21.4a	23.0ab	26.1b		Open	18	26	60	70

Values are means. Values with same letter within rows are not significantly different at $P < 0.05$.

[a] BD, soil bulk density.

[b] WHC, soil water holding capacity.

[c] EC, electrical conductivity.

Table 5 – Changes in the herbaceous plant community after *Caragana microphylla* shrub plantation establishment

Plantation age (years)	Total number of species			Total plant density (plants/m^2)			Cover (%)	Frequency (%)
	Annual	Perennial	Sum	Annual	Perennial	Sum		
0	2	0	2	10	0	10	10	70
5	4	0	4	69.3	0	69.3	10	245
13	8	0	8	392.9	0	392.9	60	447
21	10	3	13	462.6	4.8	467.4	80	567

slowly, with only a few pioneer annual species colonizing. Species number increased from two to four, and plant density from 10 to 69.3 plants/m^2, while vegetative cover did not change. In the 13-year-old plantation, eight species invaded, the cover reached up to 60% and density 392.9 plants/m^2, but all species still represented only short-lived annual grasses and forbs. In the 21-year-old plantations, cover and density increased further, and the number of species reached 13, including some perennial species.

4. Discussion

4.1. *Effects of shrubs on soil physicochemical properties*

Soils beneath woody plants are often referred to as "islands of fertility", because in their immediate surrounding area soil conditions are better than in the open grassland (Titus et al., 2002; Reynolds et al., 1999). In the present study, results showed that shrubs not only had significant "fertility island" effects, but could also improve soil texture. Contents of very fine sand, silt, clay, organic matter, total N and P, and available P were higher under shrub canopies than in open spaces. This is consistent with results from Wezel et al. (2002) and Maestre and Cortina (2002). Belsky and Canham (1994) indicated that there may be several factors that contribute to formation of "fertility islands". One of the most important factors is that shrubs are able to effectively trap fine soil material and plant detritus from nearby unprotected land (Wezel et al., 2002; Bhojvaid and Timmer, 1998). Our present results showed that in comparison with open spaces, soil silt + clay content increased by 22.0% under *C. microphylla* and 9.4% under *S. gordejvii*. These increases in fine soil particles could lead to decreased bulk density and increased soil moisture (Su et al., 2002). In the present study, compared with open spaces, soil bulk density decreased by 3.7% under *C. microphylla* and 2.4% under *S. gordejvii*, while soil moisture increased by 45.5 and 31.6%, respectively. There are differences in "fertility island" effects between *C. microphylla* and *S. gordejvii*. Possibly the main reason for this is that the former is a pinnate-leaved legume, with relatively dense branches and leaves to trap more soil fine particles and plant detritus, and the capability for N fixation which could result in higher soil N content than under non-leguminous species (Wezel et al., 2002).

4.2. *Nurse-plant effects of shrubs on herbaceous species*

Although few herbaceous plants can survive unprotected in the shifting sand dunes of Horqin Sand Land (Zhao et al., 2004), shrubs may provide protection to herbaceous plants against windblown sand, because shrub cover can reduce wind velocity and trap soil particles in transport (Gregory et al., 2001). Shrubs can also offer partial protection from herbivores by reducing access to plants living underneath their canopies (Rousset and Lepart, 1999). Thus, the shrub canopy is an important sorting factor for species present in the understory (Pugnaire and Lázaro, 2000), and some herbaceous species can be maintained under shrub canopies in shifting sand dunes (Zhao et al., 2004). In the present study, results showed that although there were no herbaceous plant species in open spaces outside shrub canopy in the shifting sand dunes investigated, *P. centrasiaticum* not only could survive under *C. microphylla* canopies, but also could successfully flower and set seed. The density, cover, height and above-ground biomass of *P. centrasiaticum* under shrub canopy were up to 107 plants/m^2, 41%, 42 cm and 219 g/m^2, respectively. Normally, *P. centrasiaticum* can survive only in fixed or semi-fixed sand dunes in Horqin Sand Land (Li et al., 2003). Its survival in shifting sand dunes is attributable to the protection afforded by shrub canopies. This is consistent with the results of Gregory et al. (2001) and Maestre and Cortina (2002).

Soil seed banks are important components of vegetation dynamics affecting both ecosystem resistance and resilience (Pugnaire and Lázaro, 2000). In arid ecosystems, seed banks are characterized by high spatial and temporal variability (Pugnaire and Lázaro, 2000), and are particularly affected by the presence of shrubs (Facelli and Temby, 2000). The present results showed that the viable soil seed bank under shrub canopies was significantly different from that in open spaces. The average seed density under shrubs was 597 seeds/m^2, and only 50 seeds/m^2 in open spaces 1–6 m outside shrub canopies, showing a decreasing trend with distance from the center of shrub canopies. This result is in agreement with studies by Moro et al. (1997). There may be several factors that contribute to seed bank patterns in shifting sand dunes. Seeds may accumulate preferentially under shrubs because shrubs can trap wind-dispersed seeds, provide protection from seed predators, and facilitate deposition by birds using them as perches (Mull and MacMahon, 1996; Pugnaire and Lázaro, 2000; Li et al., 2003). These effects show shrubs' nurse-plant roles in ameliorating the eco-environment for herbaceous species in shifting sand dunes.

4.3. *Facilitative effects of shrubs in desertified land restoration*

Results from Pugnaire and Lázaro (2000) and Maestre and Cortina (2005) suggest that in vegetation patches formed by shrubs, the effect of the canopy changes with shrub age, because both the physical protection offered by the canopy and soil organic matter and nutrients increase with time. Consistent with this, our results show that with increasing plantation age, the sand content, soil bulk density and pH decreased significantly, while silt, clay, moisture, total N and EC increased significantly, both under shrub canopies and in interspaces. Similarly, herbaceous plant species number, plant density, vegetative cover and aboveground biomass all increased significantly with increased plantation age. Similar recovery patterns have been observed in other studies examining the restoration effects of tree plantations on degraded sub-humid sites (Bhojvaid and Timmer, 1998; Wezel et al., 2002). Our results further confirm that micro-environmental nurse-plant effects of woody species on soil and herbaceous species are of great importance to restoration of desertified lands.

Some shrubs with greater resistance to wind-blown sand can remain on shifting sand dunes during grassland desertification processes (Li et al., 2003). Some herbaceous species can also persist under protective shrub canopies (Maestre and Cortina, 2005). These herbaceous species will disperse rapidly from inside to outside of the shrub canopies when external disturbance is removed or the environment is improved (Zhao et al., 2004), which will contribute to the restoration of degraded vegetation (Maestre and Cortina, 2002). In the present study, plant species number, plant density, cover and aboveground biomass of the herbaceous community under *C. microphylla* canopy increased by 350.0, 142.1, 39.0 and 12.3%, respectively, after 6 years of grazing exclusion, and by 770.0, 230.8, 87.8 and 23.7% after 13 years. Also, the average herbaceous patch diameter enlarged from 3.0 m at grazing exclusion to 19 m after 6 years and more than 22 m after 13 years. These results are in agreement with a study conducted in the Shapotou area of northwestern China (Yu et al., 2002).

Three principal mechanisms likely contributed to the colonization and development of herbaceous species in the restoration process on shifting sand dunes. First, *C. microphylla* shrubs facilitated the colonization of drought-tolerant herbaceous species by trapping and shielding wind-dispersed seeds of these species beneath their canopies and increasing the likelihood of recruitment (Li et al., 1992). Second, even where plant recruitment does not occur in open spaces, seedling establishment is often possible under the shade of existing 'nurse' shrubs, allowing the colonization and long-term persistence of some herbaceous species (Shumway, 2000). These species can then spread from beneath the shrub canopy to occupy the open-space micro-environment (Shumway, 2000; Zhao et al., 2004). Third, N-fixing legumes have been shown to increase soil nitrogen levels and to facilitate seedling growth in other successional communities in nutrient-poor environments (Shumway, 2000; Su et al., 2002). In the present study, the establishment of N-fixing *C. microphylla* resulted in significant accumulations of C and N under their canopies, producing "islands of fertility" surrounding each shrub. With increasing enclosure age, the "islands" gradually expanded into the open spaces. Therefore, *C. microphylla* in shifting sand dunes enhanced rates of colonization, enhanced the growth of other plants, and paved the way for vegetative expansion by ameliorating stressful environmental conditions.

5. Conclusion

Our results showed that in shifting sand dunes, shrubs can improve soil fertility and facilitate the establishment and growth of a herbaceous community, creating "islands of fertility" with a less harsh micro-environment. The "fertility island" effects became stronger and herbaceous vegetation patches tended to expand with increasing age of shrub plantations or grazing exclosures. This implies that shifting sand dunes in the semi-arid Horqin Sand Land can be restored to higher productivity by long-term grazing exclosure or by establishing shrub plantations on a large spatial scale.

Acknowledgements

The authors are grateful to the anonymous reviewers for their critical review and comments on drafts of this manuscript. This research was funded by the Cold and Arid Regions Environment and Engineering Institute Innovation Science Fund (O650444001).

REFERENCES

Belsky, J.A., Canham, C.D., 1994. Forest gaps and isolated savanna trees: an application of patch dynamics in two ecosystems. Bioscience 44, 77–84.

Bhojvaid, P.P., Timmer, V.R., 1998. Soil dynamics in an age sequence of *Prosopis juliflora* planted for sodic soil restoration in India. Forest Ecol. Manage. 106, 181–193.

Day, P.R., 1965. Particle fractionation and particle-size distribution. In: Black, C.A., Evans, D.D., White, J.L., Clark, F.E. (Eds.), Methods of Soil Analysis. Agronomy, vol. 9. ASA, Madison, WI, pp. 548–549.

Facelli, J.M., Temby, A.M., 2000. Multiple effects of shrubs on annual communities in arid lands of South Australia. Aust. Ecol. 27 (4), 422–431.

Gregory, S.O., Bruce, M., William, H.S., 2001. Degradation of sandy arid shrubland environments: observation, process modeling, and management implications. J. Arid Environ. 47, 123–144.

Institute of Soil Science, Chinese Academy of Sciences (ISSCAS), 1978. Physical and Chemical Analysis Methods of Soils. China Shanghai Science Technology Press, Shanghai, pp. 7–59.

Li, F.R., Zhao, L.Y., Wang, X.Z., 2003. Effects of enclosure on soil seed bank and plant community structure in sandy grassland of Horqin Sand Land. Acta Pratadculturae Sin. 12 (4), 32–40.

Li, S.G., Chang, X.L., Zhao, X.Y., 1992. A study of *Agriophyllum squarrosum*: a pioneer plant on shifting sandy land. J. Arid Land Resour. Environ. 6, 63–70.

MacArthur, R., Wilson, E.O., 1967. Theory of Island Biogeography. Princeton University Press, Princeton, New Jersey.

Maestre, F.T., Cortina, J., 2002. Spatial patterns of surface soil properties and vegetation in a Mediterranean semi-arid steppe. Plant Soil 241, 279–291.

Maestre, F.T., Cortina, J., 2005. Remnant shrubs in Mediterranean semi-arid steppes: effects of shrub size, abiotic factors and species identity on understory richness and occurrence. Acta Oecolog. 27, 161–169.

Moro, M.J., Pugnaire, F.I., Haase, P., Puigdefábregas, J., 1997. Mechanisms of interaction between *Retama sphaerocarpa* and its understory layer in a semi-arid environment. Ecography 20, 175–184.

Mull, J.F., MacMahon, J.A., 1996. Factors determining the spatial variability of seed densities in a shrub-steppe ecosystem: the role of harvester ants. J. Arid Environ. 32, 181–192.

Pugnaire, F., Lázaro, R., 2000. Seed bank and understory species composition in a semi-arid environment: the effect of shrub age and rainfall. Ann. Bot. 86, 807–813.

Reynolds, J.F., Virginia, R.A., Kemp, P.R., De Soyza, A.G., Tremmel, D.C., 1999. Impact of drought on desert shrubs: effects of seasonality and degree of resource island development. Ecol. Monogr. 69, 69–106.

Rousset, O., Lepart, J., 1999. Shrub facilitation of *Quercus humilis* regeneration in succession in calcareous grasslands. J. Veg. Sci. 10, 493–502.

Shirato, Y., Taniyama, I., Zhang, T.H., 2004. Changes in soil properties after afforestation in Horqin Sandy Land. North China Soil Sci. Plant Nutr. 50 (4), 537–543.

Shumway, S.W., 2000. Facilitative effects of a sand shrub on species growing beneath the shrub canopy. Oecologia 124, 138–148.

Simpson, R.L., Alessio, L.M., Parker, V.T., 1989. Seed banks: general concepts and methodological issues. In: Alessio, L.M., Parker, V.T., Simpson, R.L. (Eds.), Ecology of Soil Seed Banks. Academic Press, New York, NY, pp. 3–8.

Sokal, R.R., Rohlf, F.J., 1995. Biometry. W.H. Freeman, New York, NY.

Su, Y.Z., Zhao, H.L., Zhang, T.H., 2002. Influencing mechanism of several shrubs and subshrubs on soil fertility in Horqin Sandy Land. Chin. J. Appl. Ecol. 13 (7), 802–806.

Titus, J.H., Nowak, R.S., Smith, S.D., 2002. Soil resource heterogeneity in the Mojave desert. J. Arid Environ. 52, 269–292.

Wezel, A., Rajot, J.L., Herbrig, C., 2002. Influence of shrubs on soil characteristics and their function in Sahelian agro-ecosystems in semi-arid Niger. J. Arid Environ. 44, 383–398.

Yu, Y.J., Lin, Q.G., Shi, Q.H., Liu, J.Q., 2002. Changes of habitat and vegetation in man-made vegetation area of Shapotou section along Baotou-Lanzhou railway. Acta Ecol. Sin. 22 (3), 433–439.

Zhao, H.L., Zhao, X.Y., Zhou, R.L., Zhang, T.H., Drake, S., 2005. Desertification processes due to heavy grazing in sandy rangeland, Inner Mongolia. J. Arid Environ. 62, 309–319.

Zhao, H.L., Zhao, X.Y., Zhang, T.H., Wu, W. (Eds.), 2004. Desertification Processes and its Restoration Mechanisms in the Horqin Sand Land. China Ocean Press, Beijing.