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Influencing Mechanisms of Several Shrubs on Soil Chemical Properties in Semiarid Horqin Sandy Land, China

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Horqin Sandy Land is one of the serious desertification areas in the semiarid zone of north China. Shrubs are the dominant plant species in this region and they play an important role in the wind erosion-prone fragile ecosystem. This study deals with the differences of some chemical properties in the soils under shrub canopies and from adjacent open spaces and analyses their characteristics in the shrub rhizospheric soils and bulk soils. The results showed that: (1) the concentrations of organic C, total N, and total P, and the value of electrolytic conductivity (EC) in the soils under the canopy of shrubs increased by 56%, 51%, 37%, and 51%, respectively, compared with those of the soils in open spaces, but there was no significant difference in pH between the soils under shrub canopies and open spaces; (2) shrub rhizosphere soils exhibited significantly higher contents of organic C, total N, and values of EC as well as a lower value of pH compared to the bulk soils, but there was no significant difference in total P between rhizosphere and bulk soils; (3) there were close relationships between the properties in soils under shrub canopies and the rhizosphere soils, indicating that the development of "fertile islands" are favorable to root growth and induce greater amount of rhizodeposition, and vice versa; and (4) soils under Artemisia frigida *and* Caraganda microphylla *canopies and rhizospheres had significantly higher organic C and total N contents than those of* Artemisia halodendron and Salix gordejevii. *The results suggested that shrubs were of vital importance for the sequestration and accumulation of nutrients and maintenance of soil fertility in the Horqin Sandy Land ecosystem.*

Keywords Islands of fertility, rhizosphere effect, soil organic C, soil N, soil P, desertification

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Horqin Sandy Land, located in the northeastern part of China (42°41′–45°15′N, 118°35′–123°30′E, elevation 180–650 m), is one of the seriously sandy desertification areas in the semiarid agropastoral zone in northern China (Zhu et al., 1989). The primary landscape in this region was sand dune sparse steppe on interdune lowlands crisscrossed with dunes. Over the past century, especially in the recent decades, this region has undergone severe desertification due to overgrazing, excessive farming, and vegetation devastation by fuelwood gathering, resulting in a landscape having moving dunes and semi moving dunes with stabilized dunes in alternation (Wang, 2000; Zhu & Wang, 1992). Accordingly, vegetation was generally in reverse evolution process of sparse grassland → shrubs + perennial herbs → perennial herbs, wormwood artemisia steepe → wormwood artemisia, weed grassland → psammophyte vegetation. To date, the primary landscape of sparse steppe has almost disappeared completely, and shrubs have become the most significant dominant plant species (Research Group of "Study on Combating Desertification/Land Degradation in China," 1998).

Shrubs plays an important role in the degraded ecosystems in the Horqin Sandy Land. They have been used as a major source of fuelwood and forage for livestock. In desertification control, some psammophyte shrub species adaptive to nutrient poor sandy environment, such as *Artemisia halodendron* Turcz. ex Bess., *Caragada microphylla* Kom., and *Salix gordejevii* Y. L. Chang & Skvortsov, are also generally serving as pioneer species for vegetation reestablishment and for shrubby sand barrier or windbreaks for shifting sand fixation (Huang & He, 1999).

Many studies have suggested that the presence of shrubs can dramatically influence and alter the spatial distribution of nutrients (Burke et al., 1987; Charley & West, 1975; Schlesinger et al., 1996), increase soil C and N content (Barth & Klemmedson, 1978; Wezel et al., 2000; Xie & Steinberger, 2001), affect the interception, infiltration, and storage of water (Elkins et al., 1986), resulting in an overall increase in the soil fertility (Virginia & Jarrell, 1982). On one hand, in arid and semiarid desert ecosystem, shrubs protect topsoil from wind erosion and effectively trap wind-blown materials and litters within and from nearby unprotected areas. Accumulation of nutrients under shrub canopies creates "islands of fertility" (Charley & West, 1975; Garner & Steinberger, 1989), which favor increase of microorganisms, microbial activity and microbial biomass associated with fertility islands (Aguilera et al., 1999). On the other hand, shrubs generally invest more of their productivity in root material to withstand prolonged periods of stress (Lynch, 1990). The belowground production often constitutes a major part of the total net primary production in perennial shrub species (Hasson et al., 1994) and, in turn, the rhizodeposition through living roots and the production of dead roots represent the main input of organic matter to the soil. It was suggested that rhizodeposits not only can serve as a significant source of C for the microbial biomass (Grayston et al., 1996), but also will induce changes in the physicochemical characteristics of the surrounding soil, such as its concentration of nutrients, acidity, moisture, electrolytic conductivity, and redox potential (Lynch, 1990). Consequently, improvement of soil fertility under shrub canopies and rhizodeposition can provide favorable nutrient and moisture conditions for reproduction of herbal plants. As the shrubs develop islands of fertility, they are more likely to be resistant to environmental perturbation and more likely to persist in the community (Schlesinger et al., 1996). Therefore, shrubs are vital for reversing of desertification.

The development of islands of fertility and the rhizodeposition of C and N may be important strategies and mechanisms for shrubs to use nutrients effectively and adapt to severe erosion-prone sandy environments. Therefore, they are also important factors for maintaining the stability of ecosystem (Martinez-Meza & Whitford, 1996). Information about shrub-soil interaction and shrub-induced soil changes is required for a better understanding of the processes and mechanisms for reversing desertification and for appropriate management and conservation of the environment. However, this information is not available in the Horqin region. The present article reports on research to study the effects of several shrubs on accumulation of soil nutrients by exploring the fertility island and the rhizosphere effects. The questions addressed included the following pertaining to Horqin Sandy Land:

What are the magnitudes of enrichment degrees in organic C, total N and total P in soils under several shrub and subshrub canopies relative to open spaces?
What are the characteristics of soil parameters in shrub rhizosphere soils and bulk soils?
What are the differences of enrichment ratios in C, N and P among shrub species?

Materials and Methods

Site Description

The study was conducted at the Naiman Station for Desertification Research, Academia Sinica, 42° 58′N, 120°43′E, 345 m elevation, located in the southwestern end of Horqin Sandy Land, Naiman county, Inner Mongolia, north China. The climate in this region is semiarid. Mean annual precipitation is about 362 mm, nearly 70% of rainfall occurs from June to August. Mean annual temperature is about 6.8°C. The mean annual wind velocity ranges from 3.4 to 4.1 ms^{-1}, with frequent occurrence of gales (wind speed >20 m s^{-1}) in winter and spring. Geomorphologic landscape in this region is characterized by dunes crisscrossing gently undulating lowlands. The zonal soils are characterized by coarse texture and loose structure and are highly susceptible to wind erosion. The local vegetation was dominated by *Artemisia halodendron*, *Artermisia frigida* Willd., *Caragana microphylla*, *Lespedeza davurica* (Laxm.) Schindl., and *Salix gordejevii*. Shrub species have different spatial distributions and different morphological traits. *S. gordejevii* distributes on the top of semifixed sand dunes. *A. halodendron* is a pioneer psammophyte grown in shifting and semifixed sand dune stages, often appears in the degraded succession, and is generally replaced by other species in the fixed sand dune. *C. micophylla* and *A. frigida* are the major species in the fixed sand land (Zhou, 2000).

Experiment Design and Soil Sampling

In June 2001, a representative sandy land area was selected as the experimental site with semifixed sand dunes where *S. gordejevii* was distributed in clusters and adjacent fixed sandy land where *A. halodendron*, *C. micophylla*, and *A. frigida* were distributed alternatively. Sand dune height varies from 2 to 5 m. The vegetation of the selected areas was representative in the region. A 50 m × 50 m plot in the fixed sand land and a 20 m × 20 m plot in the semifixed sand dune were located. Six isolated individuals of each species growing in approximately homogenous relief in the plot with apparently morphological trait were chosen as six replications of samples. The detailed description of each species is listed in Table 1.

For the selected 24 isolated individuals of four species two sampling locations were distinguished. In the location under the shrub canopies: (A) four soil samples in perpendicular directions at a distance of about 10 cm (*A. frigida*) and 30 cm from the canopy center of shrub were taken and mixed; (B) in the adjacent open land, four soil samples in the four directions at about 10 cm (*A. frigida*) and 20 cm away from the canopy edges (outside canopy) were taken and mixed. Sampling depth was $0 \sim 10$ cm. This was done because strong wind erosion in this region led a large part of organic materials to accumulate within 20 cm (*A. frigida*) and 50 cm distance from the shrub center, and little litter remain at the edges of canopy. Under the shrub

TABLE 1 Distributed Location and Morphological Traits of Four Shrub Species Examine

Species	*A. frigida*	*A. halodendron*	*C. microphylla*	*S. gordejvii*
Family	Asteraceae, small subshrub	Asteraceae, small shrub	Fabaceae, shrub	Salicaceae, shrub
Height (cm)	$38\sim45$	$15\sim25$	$95\sim120$	$220\sim225$
Crown diamater	$28\times30\sim33\times35$	$45\times50\sim55\times60$	$90\times95\sim100\times103$	$190\times195\sim215\times220$
Numbers of shoots	$55\sim62$	$\sim$	$36\sim42$	$28\sim36$
Distributed location	Fixed sand dune	Fixed sand dune	Fixed sand dune	Semi-fixed sand dune
Growing condition	Growth luxuriance	In a degraded stage	Growth luxuriance	Growth luxuriance

canopies, the soil profile was dug to 30 cm depth (the major depth of root distribution). The rhizosphere soil (R) was collected on a plastic sheet by tapping the roots. After tapping, the soil adhering to the root surface was gently brushed off. The soil removed by tapping and brushing was combined as rhizosphere soil. The bulk soil (S) was taken from $5 \sim 30$ cm depth as close to the roots as possible.

Laboratory Analysis

All soil samples were air-dried and sieved to pass a 2-mm screen. Root particles and other organic debris were removed, then ground and sieved through a 0.25-mm sieve. Soil pH and electrolytic conductivity (EC) was determined in a 1:1 soil-water slurry and in a 1:5 soil-water aqueous extract (Multiline F/SET-3, Germany). Soil organic C (SOC) was measured by the $K_2Cr_2O_7$-H_2SO_4 oxidation method of Walkey and Black (Nelson & Sommers, 1982), total N was determined by the Kjeldahl procedure (UDK140 Automatic Steam Distilling Unit, Automatic Titroline 96, Italy), and total P spectrophotometrically (UV-1601, Japan) after H_2SO_4-$HClO_4$ digestion (ISSCAS, 1978).

Statistical Analysis

For each soil parameter we calculated the mean value of samples taken under shrub canopies (A), from nearby open land (B), rhizosphere (R), and bulk soil (S). In order to reduce the effect of intersite variability in comparison of situations A and B, we used the enrichment ratio (E_A), where $E_A = A/B$. Similarly, we calculated the ratio (E_R) between rhizosphere (R) and bulk soil (S) ($E_R = R/S$). It was calculated as the average of ratios for each pair of samples analyzed. The more E_A differs from 1, the more the soil in A differs from the soil in B. $E_A > 1$ means a higher concentration for the characteristics analyzed (or a higher value for pH and EC) in A than in B, so does E_R.

Data were analyzed using SPSS 8.0 package for significance at $P < 0.05$. Significant differences in mean soil properties analyzed in the same sampling location and the values of E_A and E_R among species were determined by analyzing replicate means ($n = 6$) with a one-way analysis of variance (ANOVA) and least significant differences (LSD). For the comparison of two variables between A and B, and R and S, the *t*-test for paired samples was performed. Pearsons correlation coefficients were calculated among all soil parameters of different sampling locations.

Results

Soil Properties under Shrubs and in Rhizospheres

The results showed that SOC, total N and P concentrations were significantly higher in soils under shrub canopies compared to soils in the adjacent open land (Table 2). The mean SOC, N, and P concentrations under the shrub canopies were increased by 54%, 51% and 37%, respectively, compared to those of the adjacent open land. Also, the mean value of EC was greater by 53% under the shrub canopies. However, pH was similar beneath and outside the canopies.

The rhizosphere soils also showed a significantly higher concentration of SOC and total N than did bulk soils. For all species, SOC and total N averaged 68% and 56% higher in the rhizosphere than in bulk soil, respectively. However, no significant difference for total P was observed ($P = 0.264$). For pH, a significant difference between rhizosphere and bulk soil was found ($P = 0.016$), but the mean pH values were lower in the rhizosphere soils by only 0.19 units. The value of EC was 2 to 3 times higher in the rhizosphere than in the bulk soil (Table 2).

TABLE 2 Means of Soil Parameters Under Shrubs (A), Nearby Open Land (B), Rhizosphere (R), and Bulk Soil (S) and Enrichment Ratios (E_A and E_B), n = 6

			Value	Enrichment Ratio		*t*-test for Pair Samples	
Variable	Unit	Location	Mean ± S.E.	E_A(A/B)	E_R(R/S)	*t*	*p*
SOC	$g \cdot kg^{-1}$	Canopy (A)	3.74 ± 1.64				
		Open land (B)	2.62 ± 1.51	1.56		7.903	<0.001
		Rhizosphere (R)	3.19 ± 1.54				
		Bulk soil (S)	1.90 ± 1.04		1.76	7.851	<0.001
Total N	$g \cdot kg^{-1}$	Canopy (A)	0.340 ± 0.131				
		Open land (B)	0.234 ± 0.106	1.51		8.474	<0.001
		Rhizosphere (R)	0.261 ± 0.131				
		Bulk soil (S)	0.167 ± 0.069		1.54	4.682	<0.001
Total P	$g \cdot kg^{-1}$	Canopy (A)	0.155 ± 0.047				
		Open land (B)	0.123 ± 0.049	1.37		3.830	0.01
		Rhizosphere (R)	0.112 ± 0.049				
		Bulk soil (S)	0.103 ± 0.025		1.08	1.145	0.264
pH(H_2O)		Canopy (A)	7.39 ± 0.23				
		Open land (B)	7.39 ± 0.26	1.00		–0.143	0.881
		Rhizosphere (R)	7.07 ± 0.50				
		Bulk soil (S)	7.26 ±0.27		0.97	−2.611	0.016
EC	$\mu s\, cm^{-1}$	Canopy (A)	73 ± 35				
		Open land (B)	48 ± 14	1.56		3.25	0.004
		Rhizosphere (R)	118 ± 64				
		Bulk soil (S)	42 ± 21		3.01	5.4	<0.001

Influence of Shrub Species on Soil Properties

Different shrub species exhibited different effects on soil properties. SOC, total N, and total P concentrations in the four sampling locations (i.e., A, B, R, S) showed marked differences in the following order: *A. frigida* = *C. micophylla* > *A. halodendron* > *S. gordejevii*. No significant differences in pH and EC were found. Among the three species distributed alternatively in the same fixed sand land, SOC and total N contents were not significantly different between soils under *A. frigida* and under *C. microphylla*, but they were significantly higher compared to those of soil under *A. halodendron*. The rhizosphere (R) for *C. micophylla* showed the higher N content than that of *A. frigida* and *A. halodendron* (Figure 1).

Influence of Shrub Species on Enrichment Ratios (E_A, E_R)

The enrichment ratios (E_A and E_R) were influenced by shrub species to a certain degree, but significant differences between species were found only for E_R of total P ($P = 0.039$) (Table 3). *S. gordejevii* and *A. halodendron* had higher values of E_A for C and P than *C. micophylla* and *A. frigida*. The N enrichment in the rhizosphere (E_R) was the highest with *C. micophylla* and the lowest with *S. gordejevii*. *A. halodendron* and *A. frigida* showed the P increase ($E_R > 1$), whereas *C. micophylla* and *S. gordejevii* showed the P decrease ($E_R < 1$) in the rhizosphere (Table 3).

Correlation between Organic C, Total N, and Total P in Different Sampling Locations

The linear correlation coefficient among most of variables was highly significant (Table 4). The highest values of coefficient *r* were found between A and B for organic C ($r = 0.909$**) and total N ($r = 0.887$**). The correlation coefficient between organic C and total N, total P of soils under shrub canopies (A) were higher than those of soils in nearby open land (B). For the rhizosphere soil and the surrounding soil (A, B, S), SOC, total N, and total P also exhibited significant correlations, except for between total P in R and total N in S. No significant correlations were observed between total N in A and B and total P in S.

Discussion

Fertile Island Characteristics

Generally, in arid and semiarid desert ecosystems, soil beneath and between shrubs may be subjected to different rates of erosion, deposition, and above- and below-ground litter inputs and its redistribution (Charley & West, 1975; Hook et al., 1991). Significantly higher concentrations of organic matter, nutrients, and microorganisms were accumulated under shrub canopies creating "fertility of islands" (Barth, 1980; Barth & Klemmedson, 1978; Burke et al., 1987, Schlesinger et al., 1996; Virginia & Jarrell, 1982; Wezel et al., 2000). In line with these findings, our results in the semiarid Horqin Sandy Land exhibited significant enrichment of SOC, N, and P under the shrubs. The enrichment ratio (E_A) of C, N, and P for several shrub species were consistent with the results obtained by Barth & Klemmedson (1978) and Wezel et al. (2000) in other regions.

Accumulation of SOC under shrub canopies resulted mainly from shrub litter inputs and redistribution of litterfall trapped by shrubs and their decomposition under canopies (Charley & West, 1975). Accumulation of total N and P was attributed to the release of N and P by decomposition of organic material. Here the chemical composition of the fallen leaves could be of some importance. Analysis showed that the fallen leaves of *C. micophylla* and *A. frigida* contain significant higher ($P < 0.001$) N content ($27.2\ g{\cdot}kg^{-1}$ and $27.7\ g{\cdot}kg^{-1}$) than that of *A. halodendron*

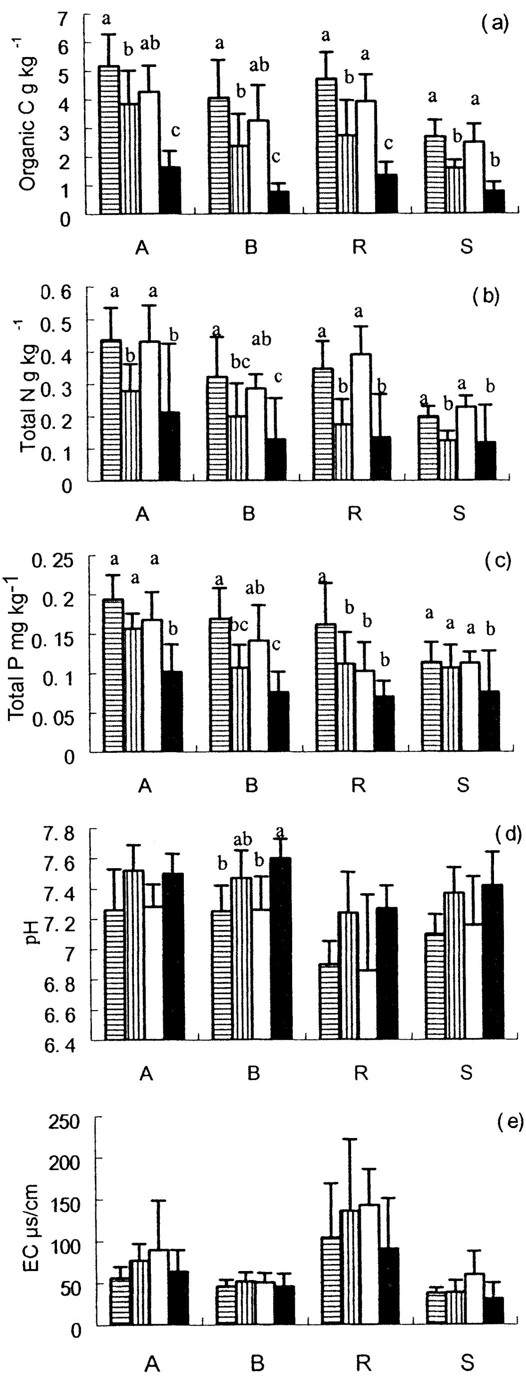

FIGURE 1 Chemical characteristics (mean ± SD) of soil samples taken underneath (A) and outside (B) of shrub canopy, rhizosphere (R) and bulk soil (S) of four shrub species in the Horqin sandy land: (a) organic C, (b) total N, (c) total P, (d) pH, (e) electrolytic conductivity (EC). Different letters among species at the same sampling area indicate significant statistical differences at $p < 0.05$.

TABLE 3 Enrichment Ratio of Soil Parameters for Different Shrub Species

	A. frigida		*A. halodendron*		*C. microphylla*		*S. gordejvii*		ANOVA	
Variable	E_A	E_R	E_A	E_R	E_A	E_R	E_A	E_g	$P(E_A)$	$p(E_R)$
SOC	1.33	1.86	1.86	1.95	1.31	1.61	1.84	1.62	0.122	0.586
Total N	1.38	1.73	1.50	1.44	1.57	1.80	1.61	1.19	0.442	0.122
Total P	1.18	1.40	1.54	1.11	1.33	0.91	1.45	0.92	0.430	0.039*
pH	1.00	0.98	0.98	0.97	1.00	0.96	0.99	0.98	0.832	0.879
EC	1.31	2.67	1.58	3.33	1.93	3.26	1.41	2.78	0.614	0.773

TABLE 4 Pearson Linear Correlation Coefficients (r) Between C, N, P Content in Soils of the Different Location

		SOC				Total N				Total P		
Item	Sampling Location	A	B	R	S	A	B	R	S	A	B	R
SOC	B	0.909**										
	R	0.730**	0.840**									
	S	0.777**	0.895**	0.888**								
Total N	A	0.775**	0.653**	0.629**	0.648**							
	B	0.764**	0.713**	0.598**	0.637**	0.887**						
	R	0.646**	0.712**	0.830**	0.749**	0.746**	0.707**					
	S	0.524**	0.540**	0.578**	0.659**	0.740**	0.667**	0.687**				
Total P	A	0.669**	0.594**	0.658**	0.631**	0.634**	0.539**	0.694**	0.420*			
	B	0.657**	0.655**	0.627**	0.604**	0.711**	0.874**	0.711**	0.453**	0.635**		
	R	0.738**	0.769**	0.542**	0.711**	0.560**	0.614**	0.597**	0.290	0.711**	0.702**	
	S	0.601**	0.741**	0.668**	0.780**	0.372	0.382	0.602**	0.412*	0.606**	0.459**	0.645**

*,** significant at $P \le 0.05$, $P \le 0.01$, respectively, n = 24.

($10.1\,g{\cdot}kg^{-1}$) and *S. gordejevii* ($7.5\,g{\cdot}kg^{-1}$). This was correlated with the distribution of soil N under shrubs. Also, accumulation of N and P under shrubs, to a lesser degree, resulted from the deposition of wind-blown fine particle fractions enriching with nutrients. Soil silt and clay content under canopies was 16% higher than that of outside canopies. Significant correlation between organic C and total N and total P in soils under shrubs (r = 0.775** and 0.699**, respectively) indicated that higher concentration of N and P are linked to the higher concentration of organic matter in soils under shrubs because soil organic matter concentration is one of the most important factors in the storage of nutrients in these nutrient-poor sandy soils (Wezel et al., 2000). Significant enhancement of EC may be related to the released nutrient ions by decomposition of organic materials under shrubs. No difference of soil pH was observed. Our interpretation was that the apparent periodic addition of eolian soil material under the shrub, as well as relatively homogeneous moisture content in the surface soils may have been important factors in the lack of pH changes.

Different shrub species had a different response to the enrichment ratio. Higher enrichment ratios were found for C and N under *S. gordejevii* and *A. frigida*, and for N under *C. halodendron*. This seemed to have resulted from the differences in the chemical composition of shrub litter and its mineralization (Charley & West, 1975; Wezel et al., 2000). It might also be related to the differences in soil environments where shrub species were distributed, as well as to their morphological traits. *S. gordejevii* was distributed on the top of semifixed sand dunes. The soils in the adjacent open land exhibited low levels of nutrients due to almost complete loss of fine materials under strong wind erosion, resulting in substantial differences of C and N between soils under shrubs and in the open land (Figure 1). *A. halodendron* is a native pioneer perennial shrub that grows mainly on shifting and semifixed sandy land and it is in the severe retrogressive succession in fixed sand land due to inter-species competition and its clonal propagation traits (Li, 1991). Although its appearance with scattering and creeping stems and openly foliated crown are unfavorable to trapping of litter and eolian erosion materials, relatively longer periods of development of islands of fertility (clear microtopographic mounds under shrubs) probably lead to higher enrichment ratio of C and N. Higher N enrichment ratio under *C. microphylla* may also be attributed to its N_2 fixation.

Significant relationships between organic C and total N of soils under shrubs and of nearby open land indicated that soil fertility in the vicinity of the shrubs could get improvement to a certain degree with the development of shrub crown due to a reduction of wind-erosion. It is also suggested that different species have different adaptation characteristics on soil fertility in the process of colonization and growth. *A. halodendron* and *S. gordejevii* may be able to adapt to a poor-nutrient sandy soil environment, whereas *A. frigida* and *C. microphylla* may have relatively higher nutrient requirements.

Rhizosphere Characteristics

Shrub plants have well-developed roots, and a significant part of the organic materials photosynthesized in the aerial organs of the plant is released by the roots into the soil, contributing to C and N sequestration. SOC and total N content in the rhizosphere was significantly higher than those in the bulk soil (Table 1), indicating that a large amount of organic substrates, such as exudates, secretions, sloughed cells, and mucilage could be released from roots and deposited in the root micro-environments (Lynch & Whipps, 1990). The results also indicated that the shrubs and subshrubs in desert ecosystem exhibited significantly greater quantities of C and N rhizodeposition compared to those of sorghum in agro-ecosystems. There were significant differences ($P < 0.001$) between rhizosphere and bulk soil. The rhizodeposition was higher than of some tree species (*Pinus tabulaeformis*, *Pinus* *armandi*, *Laxix orincipis-rupprechtii*) in forest ecosystems (Lee et al., 1997; Liu et al., 1998; Yang et al., 1999). A rational interpretation probably is that the perennial desert shrubs invest more of their productivity in root material to withstand prolonged periods of stress (Lynch & Whipps, 1990). In addition, N deficiency and/or P deficiency, especially in desert ecosystem, increased the release of organic C from roots (Petersen & Bottger, 1991).

Difference in pH between the rhizosphere and the bulk soil was significant, but no changes were observed among soils under shrubs (A), from the open land (B), and bulk soils (S) (Table 2). This indicated that plant roots induced the change of pH.

No significant statistical differences of rhizosphere effect (E_R) among the shrub species were found except for P in this study, but different species differed in their rhizodeposits to a certain extent (Figure 1). This might be attributed to the difference of their soil environment factors and nutritional-mediated control of shrub species. Close correlation between the concentration of C and N in the rhizosphere (A) and that in the soils under shrub canopies (R) indicated that the accumulation of C and N under shrubs clearly affected nutrient uptake by the roots and C and N rhizodeposition, and vice versa. Therefore, *S. gordejevii*, growing in the semifixed sand dune having poor nutrient content, had the lowest values of E_R for C and N. In contrast, *A. frigida* had higher values of E_R for C and N. In addition, *C. microphylla*, a leguminous shrub, had a number of nodules in the roots. Its function of N_2 fixation may have resulted in a higher accumulation of N in the rhizosphere than in that of no N_2-fixing species. Further, greater amounts of C are transferred to roots with ectomycorrhizae compared with nonmycorrhizal plants (Reid et al., 1983). This could lead to the increase of C rhizodeposition. *A. halodendron* is in the severe retrogressive succession in fixed sand land, and its higher value of E_R for C resulted mainly from some floccules adhering to the coarse surface of aged main root and the great amount of sloughed materials from aged root. The discrepancies among shrub species for the dynamics of total P in the rhizosphere may be possibly related to hereditary physiological traits of species, nutrient requirements and root morphological structure (Van der Krift et al., 2001; Yan et al., 1992), except for the errors resulting from sampling methods.

Conclusion

The results showed that: (1) soils under shrub canopies had significantly higher concentrations of SOC, N, and P compared to the soils from adjacent open lands; (2) the contents of SOC and N were significantly higher in the shrub rhizosphere soils than the bulk soils; and (3) shrub species had a different response to soil fertility—soils under *A. frigida* and *C. microphylla* canopies and rhizospheres had significantly higher organic C and N levels than those of *A. halodendron* and *S. gordejevii*. The results suggested that shrubs in the Horqin Sand Land ecosystem were vital for the sequestration and accumulation of carbon and nitrogen. If desertification is to be reversed, increased emphasis on management of shrubs will be necessary.

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