Spatial distribution of soil nutrients after the establishment of sand-fixing shrubs on sand dune

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ABSTRACT

Caragana microphylla Lam., an indigenous leguminous shrub, was the dominant plant species to be used to control desertification in semi-arid Horqin Sandy Land. To elucidate the cover effect of *Caragana microphylla* planted for 25 years on spatial distribution of soil nutrients including C, N, P and K, soil samples were taken from four soil depths (0–5 cm, 5–10 cm, 10–20 cm, and 20–40 cm) and three slope positions (windward slope, top slope, and leeward slope). Soil nutrients under shrubs (US) and between shrubs (BS) were compared to investigate the enrichment effect of plantation. The results showed that soil nutrients except total K were significantly higher in surface soil (0–5 cm) than in deeper layer soil ($P < 0.01$). Significant differences were found in the contents of total organic carbon, total nitrogen, total phosphorus, and total K at different slopes. The contents of total organic carbon and total nitrogen were higher in US than in BS ($P < 0.05$), but pH was lower ($P < 0.01$). Our results indicated that the establishment of *Caragana microphylla* increased the accumulation of soil nutrients, and played an important role in restoring sand dune ecosystems.

Keywords: *Caragana microphylla*; sand dune; soil nutrients; spatial distribution

The Horqin Sandy Land is one of the most severe desertification areas in China. Although the trend of desertification slows down, the area of sandy land is still expanding. Vegetation restoration is one of the most common and effective ways to combat and control desertification (Su et al. 2005). Severe desertification could be reversed by establishing suitable vegetation on a large spatial scale (Cao et al. 2008).

In recent years, many studies on the plant cover effect on soil properties of sandy land have been done (Su et al. 2005, Zhao et al. 2007). Bochet et al. (1999) argued that the positive inter-feedback between shrub and soil permitted the shrub islands to become more resistant to degradation process. The presence of shrubs strongly influenced micro-site soil characteristics and resulted in higher nutrient levels in sandy land (Titus et al. 2002). The improvement of soil nutrient by vegetation was mainly through the decomposition of organic residues and the absorption of nutrients that have been leached from the surface (Antunes et al. 2008). However, most studies of this matter had been carried out in the surface soil of 0–10 cm, and recently few were conducted on spatial distribution of soil nutrients with different soil depths and slope positions in sand dune ecosystem. Zhang et al. (2006) in the semiarid Horqin Sandy Land found that soil properties at shrub individual scale exhibited significant spatial variations. The spatial pattern of soil properties was critical for shaping water and nutrient flows in semiarid ecosystems. Soil organic carbon and total nitrogen of stable sand dunes are closely associated with vegetation cover. Therefore, the analysis of spatial heterogeneity in soil nutrients can reflect the action range and extent of sand-fixing herbs and will be helpful for understanding the ecological relationship between soil and environment (Rossi et al. 1992, Zuo et al. 2008).

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Caragana microphylla Lam., the leguminous shrub, was distributed widely in the Horqin Sandy Land. It also serves as the pioneer species for vegetation reestablishment and moving sand fixation to control desertification (Li et al. 2002). To clarify the cover effect of *C. microphylla* with 25 years in stable sand dune of Horqin Sandy Land, the spatial distribution of soil nutrients were investigated. The main objectives of our study were: (1) to investigate the spatial variation of soil nutrients in a sand dune due to the establishment of *Caragana microphylla*; (2) to analyze and evaluate the contribution of *Caragana microphylla* to improve soil nutrients.

MATERIAL AND METHODS

Study area description. This study was conducted at the Wulanaodu Experimental Station of Desertification (43°02'N, 119°39'E), Chinese Academy of Sciences. The Station is located in the western Horqin Sandy Land of Northeast China. The annual mean temperature is 6.3°C, and the frost-free period is 130 days. The annual mean precipitation is 340.5 mm, with 70–80% of precipitation between May and September, and the annual mean pan-evaporation is around 2500 mm. The landscape is characterized by gently undulating, shifting and semishifting sand dunes with inter-dune bottomlands. The soil at our experimental sites is Ustic-Sandic Primosol. Average annual wind velocity varies between 3.2 m/s and 4.5 m/s, with the frequent occurrence of gales (wind speed > 20 m/s) in winter and spring. Prevailing wind direction is Northwest (Jiang et al. 2007).

Species description. *Caragana microphylla*, an indigenous leguminous shrub, was the dominant plant species used to restore vegetation and control desertification in semi-arid Horqin Sandy Land. It was artificially planted on desertified sandy land around Wulanaodu from 1983. Before planting, the vegetation cover was generally less than 5%. *C. microphylla* grew to form 1 m high shrubby belts 3–5 years after planting (Cao et al. 2008).

Experiment design and soil sampling. The research was carried out in stable sand dune with 25-year-old *C. microphylla* plantations on April 24, 2008. The sampling period was spring, the beginning of the growing season and rain season. Soil environment was relatively stable and was seldom affected by wind and other factors. In our experiment, three slope positions (middle part of windward slope, top slope, and middle part of leeward slope) were selected as the experimental sites. On each slope, we chose sampling plots under shrub (US) and between shrub lands (BS) of *C. microphylla* with the same growth situation, respectively. Four soil samples, 20 cm from center of the shrub or 20 cm apart from the edge of shrub, were taken out in four directions, and mixed as a pool sample of under shrub (US) or between shrubs (BS), respectively. Soil samples were taken at the depth of 0–5 cm, 5–10 cm, 10–20 cm and 20–40 cm with a 5 cm diameter soil auger, respectively. Four transects as four replications, each 10 m apart, were run through the sand dune system. A total of 96 soil samples (3 slopes × 2 'BS and US' × 4 soil depths × 4 replications) were collected. After sampling, the soils were stored in individual plastic bags and immediately kept at 4°C. Soil samples were hand-sieved through a 2-mm screen to remove roots and discarded. Fresh soils were used to determine soil moisture. One part of soils was air dried for the analysis of soil chemical properties. Soil moisture of air dried soil was also determined in order to calculate soil chemical properties (C, N, P, K) based on oven dried soil mass (expressed as gram per kilogram dry soil).

Laboratory analysis. Soil moisture (SM) was determined gravimetrically by drying samples at 105°C for 48 h. Soil pH and electrical conductivity (EC) were measured in a soil-water suspension (1:2.5 and 1:5 soil-water ratio, respectively) with pH analyzer (FE20/EL20, METTLER TOLEDO, Shanghai, China) and 150A EC analyzer (Thermo Electron Corporation, USA). Soil total organic carbon (C_{TOT}) was measured by dry combustion, using an SSM-5000A solid sample module for a TOC5000/5050. Soil total nitrogen (N_{TOT}) was determined by Kjeldahl digestion. C/N (g/g) = total organic carbon (g/kg)/total nitrogen (g/kg). Soil total P (P_{TOT}) and soil total K (K_{TOT}) were analyzed by Spectrophotometer (Unico 7200, Shanghai, China) and Flame photometer (FP 640, Shanghai, China), respectively (Lu 2002).

Statistical analysis. All results are reported as mean ± standard deviation. All data were analyzed using SPSS software package (SPSS Inc., Chicago, IL, USA). Multiple comparisons and analyses of variance (ANOVA) were used to determine the differences among the treatments. Pearson correlation coefficients were used to evaluate relationships between the corresponding variables. Differences at $P < 0.05$ were considered significant. Enrichment ratio E = US/BS, US is the value of soil property under shrub and BS is between shrubs (Su et al. 2002). The *t*-test was used to show enrichment effect (the difference between US and BS).

RESULTS AND DISCUSSION

Spatial distribution of soil moisture, pH and electrical conductivity. The values of soil moisture (SM), electrical conductivity (EC) and soil pH at different soil depths (0–5 cm, 5–10 cm, 10–20 cm, and 20–40 cm) on each slope are shown in Figure 1. The values of SM were higher under shrubs (US) than between shrubs (BS) at the depth of 0–10 cm. SM decreased sharply with increasing soil depth at three slope positions. SM of US on windward slope decreased significantly from 9.95% at the 0–5 cm depth to 1.26% at the 20–40 cm depth; on the leeward slope, SM of BS decreased from 5.20% at the 0–5 cm depth to 2.50% at the 20–40 cm depth. Only at the 0–5 cm depth, a significant difference in SM was shown among three slope positions ($P < 0.05$). It suggested that depth effect on SM was more significant than slope effect. EC values in the stable sand dune ranged from 71.73 µS/cm to 18.25 µS/cm. The values of EC were significantly higher under shrubs than between shrubs ($P < 0.01$) at the 0–20 cm depth, but not at the 20–40 cm depth ($P > 0.05$) on each slope. Significant differences in EC were also observed among different soil depths. Soil pH was significantly different among different slope positions and soil depths ($P < 0.05$). The pH values were significantly lower under shrubs than between shrubs ($P < 0.01$).

The significant differences in spatial distribution of SM, EC and pH mainly appeared in different soil depths and between US and BS, which suggested the significant effect of shrubs on soil properties. Su and Zhao (2003) proved that shrub canopy reduces transpiration and the establishment of *Caragana microphylla* in sand dune can increase soil water holding capacity. Our results were in agreement with the findings of Su et al. (2002) that the lower EC in the deeper soil layer reflected the accumulation and deposition of soluble salts in litters after the establishment of shrub, especially under the shrub canopies. The extensive secretion of organic acids and the release of CO_2 from litters, roots, and microorganisms can lead

Table 1. Spatial distribution of soil nutrients in the stable sand dune (mean ± SD)

Soil nutrient (g/kg)	Soil depth (cm)	WS		TS		LS	
		US	BS	US	BS	US	BS
C_{TOT}	0–5	6.36 ± 0.66^a	5.69 ± 0.66^a	4.33 ± 0.15^a	3.44 ± 0.26^b	3.93 ± 0.39^a	2.91 ± 0.28^b
	5–10	3.10 ± 0.40^a	2.81 ± 0.36^a	2.01 ± 0.30^a	1.41 ± 0.16^b	2.44 ± 0.21^a	1.45 ± 0.15^b
	10–20	1.16 ± 0.15^a	0.94 ± 0.16^a	0.89 ± 0.09^a	0.71 ± 0.04^b	0.83 ± 0.05^a	0.72 ± 0.13^a
	20–40	0.65 ± 0.08^a	0.60 ± 0.04^a	0.45 ± 0.05^b	0.52 ± 0.05^a	0.59 ± 0.05^a	0.44 ± 0.04^b
	P	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
N_{TOT}	0–5	0.75 ± 0.14^a	0.67 ± 0.11^a	0.60 ± 0.11^a	0.42 ± 0.03^b	0.52 ± 0.02^a	0.40 ± 0.04^b
	5–10	0.35 ± 0.03^a	0.37 ± 0.03^a	0.26±0.02^a	0.24 ± 0.02^a	0.25 ± 0.02^a	0.25 ± 0.02^a
	10–20	0.15 ± 0.01^a	0.13 ± 0.01^a	0.11±0.02^a	0.10 ± 0.01^a	0.11 ± 0.01^a	0.09 ± 0.01^a
	20–40	0.11 ± 0.01^a	0.10 ± 0.01^b	0.09±0.01^a	0.07 ± 0.01^b	0.08 ± 0.01^a	0.08 ± 0.01^a
	P	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
P_{TOT}	0–5	0.22 ± 0.04^a	0.22 ± 0.03^a	0.14 ± 0.02^a	0.11 ± 0.02^b	0.14 ± 0.02^a	0.14 ± 0.02^a
	5–10	0.17 ± 0.01^a	0.17 ± 0.01^a	0.10 ± 0.01^a	0.10 ± 0.01^a	0.11 ± 0.02^a	0.14 ± 0.01^a
	10–20	0.12 ± 0.02^a	0.11 ± 0.01^a	0.08 ± 0.01^a	0.07 ± 0.01^a	0.10 ± 0.01^a	0.10 ± 0.02^a
	20–40	0.08 ± 0.02^a	0.09 ± 0.01^a	0.05 ± 0.01^a	0.07 ± 0.02^a	0.09 ± 0.02^a	0.08 ± 0.01^b
	P	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
K_{TOT}	0–5	26.98 ± 0.37^a	27.20 ± 0.42^a	27.39 ± 0.44^a	27.57±0.97^a	30.97 ± 1.37^a	28.66 ± 0.76^a
	5–10	27.30 ± 0.82^a	28.33 ± 1.05^a	27.53 ± 0.98^a	27.69 ± 0.68^a	26.74 ± 0.46^b	30.52 ± 0.44^a
	10–20	28.79 ± 0.42^a	30.43 ± 1.64^a	28.55 ± 0.33^a	25.48 ± 1.09^b	26.08 ± 0.73^a	27.84 ± 0.69^a
	20–40	29.74 ± 0.78^a	26.86 ± 0.79^b	29.75 ± 0.59^a	26.03 ± 1.32^b	30.63 ± 0.76^a	18.46 ± 0.69^b
	P	< 0.01	< 0.01	< 0.01	< 0.05	< 0.01	< 0.01

WS – windward slope; TS – top slope; LS – leeward slope; US – under shrub; BS – between shrub lands. Significant differences ($P < 0.05$) between US and BS treatments in individual soil depth and slope positions were indicated with different letters (^{a} and ^{b})

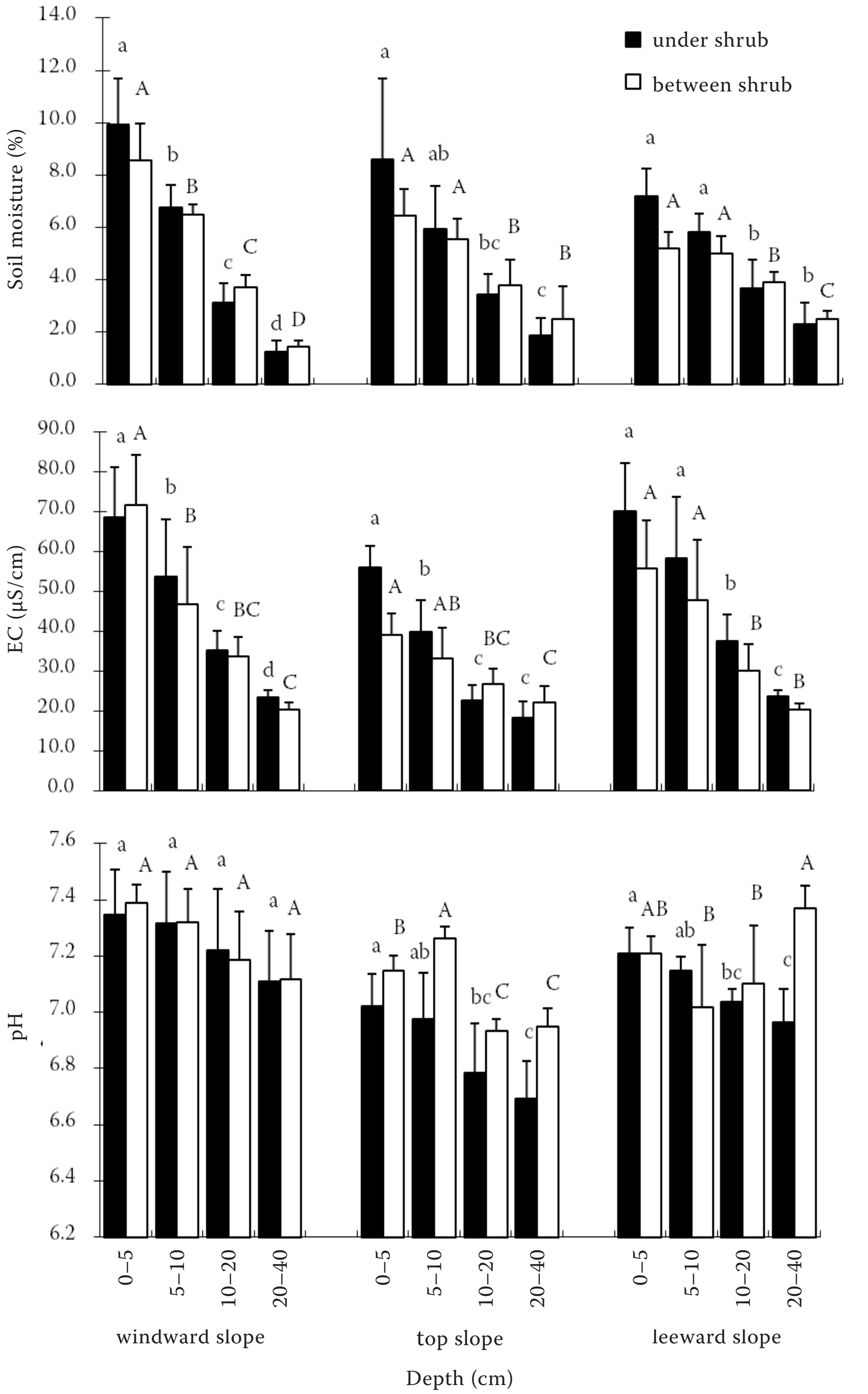

Figure 1. Spatial distribution of soil moisture, pH and EC at different slope positions. Different small/capital letters indicate significant differences in different soil depths on each slope of US/BS

to a decrease of pH (Morel and Hinsinger 1999, Tornquist et al. 1999). These results all proved the cover effect of sand-fixing shrubs in improving the SM, EC and pH.

Spatial distribution of soil nutrients. The spatial variations in soil C_{TOT}, N_{TOT}, P_{TOT} and K_{TOT} are shown in Table 1. The values of C_{TOT}, N_{TOT} and P_{TOT} decreased with increasing soil depth. The values of

C_{TOT}, N_{TOT}, and P_{TOT} were higher on windward slope than on top and leeward slopes. Significant differences in C_{TOT}, N_{TOT}, P_{TOT} and K_{TOT} were found ($P < 0.05$) among different depths. The contents of soil C_{TOT} were significantly higher in US than that in BS at 0–20 cm of top slope, and 0–10 cm and 20–40 cm of leeward slope ($P < 0.05$). Significant differences between US and BS were observed for N_{TOT} at 0–5 cm of top and leeward slope and 20–40 cm of windward and top slope ($P < 0.05$), and for P_{TOT} at 0–5 cm of top slope and 20–40 cm of leeward slope. There were also significantly higher K_{TOT} values in US than that in BS at 10–20 cm of top slope and 20–40 cm of all three slopes ($P < 0.05$). The variation ranges of C:N ratios were relatively larger under shrubs than between shrubs (Figure 2). The values of C:N ratios were higher under shrubs than between shrubs. Significant differences in the values of C:N ratios were observed among different slope positions.

More sand-fixing shrubs were established on windward slope so as to control wind erosion, and plantation densities played an important role in nutrient enrichment, which was probably the reason why soil nutrients were high on windward slope. Topography affected the soil water content, soil organic C and total N at sites from dune top to bottom, and partly contributed to the distribution of soil properties in the sand dune ecosystem (Zuo et al. 2008).

It can be explained that the contribution of *C. microphylla* to improve soil nutrients mainly through two ways. One is the physical way, the establishment of *C. microphylla* trapped wind-blown fine materials and dust which were rich in nutrients and deposited in the surface soils under their canopies (Su et al. 2004). The other is chemical way. For example, the N released by litter decomposition resulted in an increase in soil N. The development of herbs formed an important component of net primary productivity, and their rapid growth and death provided an important input of C, N and other nutrients (Cao et al. 2008). Root architecture of shrubs plays a key role through both physical and chemical ways in improving soil nutrient. Larger of roots of *C. microphylla* appeared at 20 cm soil layer in US and beneath 50 cm soil layer in BS. More roots had larger contact area with soil and possessed stronger sand fixation ability. Root system of *C. microphylla* with a lot of nodules could fix the free nitrogen and increased the contents of soil nitrogen (Cao et al. 2004). The number and biomass of roots affected the distribution range of soil nutrient (Hansson et al. 1994, 1995). These were the reasons why soil nutrients were significant among different soil depths and between US and BS in our study.

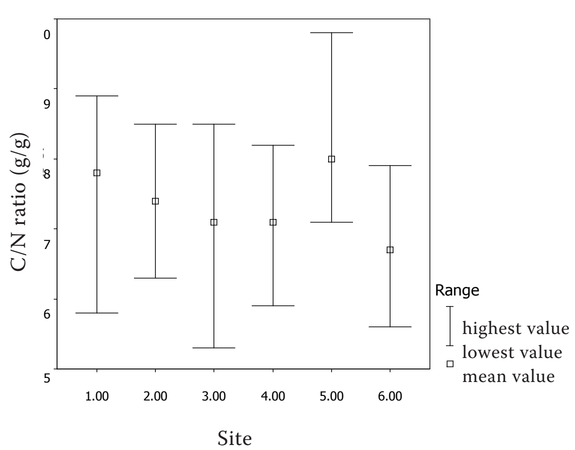

Figure 2. Changes of C:N ratio from US and BS at different slope positions. Site axe (X axe): site 1 and 2 represent US and BS on the windward slope, respectively; site 3 and 4 represent US and BS on the top slope, respectively; site 5 and 6 represent US and BS on the leeward slope, respectively

During the decomposition process of litter under the shrub canopy, the release rate of C in litter was faster than that of N. Due to the difference of wind erosion, falling dust and other impact factors, C_{TOT} and N_{TOT} varied with increasing slope elevation (Thompson et al. 2005), and the change in soil properties reflected the variation of microenvironment in different slope positions.

Enrichment ratios. Enrichment ratio (E) may indicate typical shrub fertile island phenomenon in semi-arid region (Garner and Steinberger 1989). The effects of the establishment of *C. microphylla* in sand dune on soil nutrients can be shown with enrichment ratio (Table 2). The enrichment ratios of C_{TOT} and N_{TOT} were higher than that of P_{TOT} and K_{TOT}. Significant differences in the enrichment effect on C_{TOT} and N_{TOT} were found ($P < 0.05$), but not on P_{TOT} and K_{TOT}.

The establishment of *C. microphylla* had different influence on different nutrients in sandy land soil. In many arid and semi-arid ecosystems, canopy shrubs have a strong positive influence on soil moisture and nutrient availability, creating islands of fertility where organic matter and nutrients are high relative to areas outside the canopy (Schade and Hobbie 2005). In our study, *C. microphylla* can enrich C and N under their canopy, and typical 'fertile islands' phenomenon also appeared in soil under canopy. In immediate

Table 2. Enrichment ratios of soil nutrients in the stable sand dune

Variable (g/kg)	Position	Mean ± SD	Enrichment ratio E (US/BS)	*t*-test for paired samples	
				t	*P*
C_{TOT}	US	2.23 ± 1.08	1.27 ± 0.24	3.829	< 0.01
	BS	1.80 ± 0.92			
N_{TOT}	US	0.28 ± 0.14	1.18 ± 0.17	2.266	< 0.05
	BS	0.24 ± 0.10			
P_{TOT}	US	0.12 ± 0.02	1.01 ± 0.22	0.000	NS
	BS	0.12 ± 0.02			
K_{TOT}	US	28.37 ± 0.92	1.05 ± 0.20	1.078	NS
	BS	27.09 ± 1.80			

US – under shrub; BS – between shrubs; NS – no significant difference

surrounding area beneath plants, soil conditions are better compared to the soils between shrubs (Wezel et al. 2000).

Correlation coefficients between soil nutrients and soil moisture, pH and EC. Correlation analysis between soil nutrients and soil moisture, pH and EC in the stable sand dune is shown in Table 3. SM, pH and EC were correlated positively with C_{TOT}, N_{TOT} and P_{TOT} ($P < 0.01$), but not with K_{TOT}. The highest correlation coefficient appeared between soil moistures and N_{TOT}. The study of Xie and Steinberger (2001) also proved that there was a positive correlation between soil moisture and soil nitrogen in a soil desert ecosystem, and nitrogen levels governed mainly by soil moisture.

In conclusion, the contribution of *Caragana microphylla* plantation was manifested by the significant increase of soil moisture and soil nutrients in the surface soil under shrubs. The differences of soil nutrients between US and BS showed the fertile island phenomenon forming in soil beneath shrubs. The spatial patterns of soil nutrients had significant feedbacks to the long-term establishment of sand-fixing shrubs. Vegetation restoration promoted the accumulation of soil nutrients and their spatial dependence. Spatial effect (including soil depth, slope position, US and BS) reflected the influence range and extent of *C. microphylla* on soil nutrient. In the stable sand dune of Horqin Sandy Land, *Caragana microphylla* was of vital importance for the accumulation of nutrients and maintenance of soil fertility and played an important role in controlling desertification.

Table 3. Correlation coefficients between soil nutrients and soil moisture, pH and EC in the stable sand dune

	SM	pH	EC
C_{TOT}	0.858**	0.428**	0.816**
N_{TOT}	0.895**	0.409**	0.816**
P_{TOT}	0.793**	0.525**	0.792**
K_{TOT}	0.022	–0.219	0.136

* $P < 0.05$, ** $P < 0.01$

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