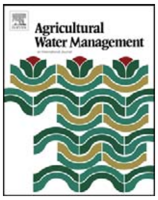
Agricultural Water Management 97 (2010) 1978–1986

Contents lists available at ScienceDirect

Agricultural Water Management

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



Enrichment of soil fertility and salinity by tamarisk in saline soils on the northern edge of the Taklamakan Desert

Chuan Hua Yin [a,b], Gu Feng [a,b,*], Fusuo Zhang [b], Chang Yan Tian [a], Caixian Tang [c]

[a] Key Laboratory of Oasis Ecology and Desert Environment, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China
[b] College of Natural Resources and Environmental Sciences, China Agricultural University, Beijing 100094, China
[c] Department of Agricultural Sciences, Latrobe University, Bundoora, Victoria 3086, Australia

ARTICLE INFO

Article history:
Available online 9 April 2009

Keywords:
Fertile islands
Islands of salinity
Tamarisk
Taklamakan Desert
Saline agriculture

ABSTRACT

To better understand the influence of *Tamarix* spp. (tamarisk shrubs) on soil fertility and salinity and the implication for saline soil management in northwestern China, several soil physical and chemical characteristics were measured beneath tamarisk canopies from the upper, middle, and lower regions of the Taklamakan Desert alluvial plain. The measured properties included soil organic matter (SOM), plant-available phosphorus (P), extractable soil potassium (K) soil electric conductivity (EC), sodium (Na^+), total potassium (K^+), and pH. The enrichment ratios for soil nutrients (i.e., available P, extractable K, and SOM) and salinity (i.e., EC, Na^+, K^+, and pH) were used to evaluate fertility and salinity islands in tamarisk mounds. SOM, available P, and extractable K were higher within mounds than in open, tamarisk-free land in each of the three sampled locations. The SOM enrichment ratios were highest at the middle region of the alluvial plain and lowest at the lower region of the alluvial plain, a pattern that is consistent with the growth patterns of tamarisk plants. The variation in SOM enrichment ratios in surface soils was mainly affected by the shoot biomass of tamarisk shrubs. The positive effect of tamarisk on soil fertility indicates that tamarisk may be beneficial for vegetation restoration and improving utilization of saline land. Nevertheless, soil salinity and pH increased under tamarisk canopy, especially EC and K^+ in surface soil from the middle alluvial plain. The EC enrichment ratio was highest in the middle alluvial plain and, depending on soil depth, lowest in the upper and lower alluvial plain. These results reflect negative effects of tamarisk on soil chemical characteristics.

1. Introduction

Tamarix spp. (tamarisk shrubs) are considered one of the ten worst weeds in the United States (Grubb et al., 1997) and are listed as noxious weeds in Montana because of their many adverse effects on the environment. These effects include altering the chemical and physical conditions of their immediate environment as well as larger-scale effects on the entire invaded ecosystem (Ellis, 1995; Di Tomaso, 1998; Zavaleta, 2000). Several researchers have suggested that salt exudates from tamarisk cause salinization of soil beneath their canopy (Brotherson and Field, 1987; Grubb et al., 1997). Salinization deters the growth of less tolerant native species, degrades wildlife habitat, and causes excessive consumption of groundwater (Brotherson and Field, 1987; Grubb et al., 1997). Anderson (1998) and Tomar et al. (2003), however, showed that tamarisk does not induce salinity accumulation in surface soils; islands of salinity form due to capillary action and/or irrigation with saline water. An additional study also indicated that salinization of soils did not occur beneath tamarisk canopy and further suggested that tamarisk has a fertilizing effect on the underlying soil (Lesica and DeLuca, 2004). The increase in soil fertility may have been due to leaf secretions, litterfall, or both (Lesica and DeLuca, 2004). Besides increasing soil fertility, tamarisk also has other positive benefits. For example, tamarisk provides habitat for nesting birds or can be used as ornamental and shade trees, in windbreaks, in erosion stabilization projects, and in the production of honey. These positive effects are, in part, the reasons that tamarisk was identified as a key species in preventing or minimizing desertification, especially in the southern Xinjiang, China arid zone (Liu, 1996).

The Taklamakan Desert, which lies in southern Xinjiang, China, is the largest sandy desert in China and the second largest in the world (Zhu et al., 1981). This desert is also one of the three main sources of dust storms in East Asian (Yan et al., 2002). Therefore, protection and rehabilitation of degraded desert ecosystem

---

* Corresponding author at: College of Natural Resources and Environmental Sciences, China Agricultural University, 2 Yuanmingyuan West Road, Beijing 100094, China. Tel.: +86 10 62733885; fax: +86 10 62731016.
E-mail address: fenggu@cau.edu.cn (G. Feng).

0378-3774/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.agwat.2009.02.013

components are critical to this region and have received much attention in recent years (Arndt et al., 2004; UNEP, 1997; Yang, 2001). Within and around the Taklamakan Desert, tamarisk is an important halophytic shrub in windbreaks and sand-fixes, and this shrub can be used for development of saline agriculture. As a major weed species in riparian areas of desert environments, however, many studies have been conducted on tamarisk shrubs in the United States (Busch and Smith, 1995; Vitousek, 1990). The role of tamarisk communities in capturing resources and the development of soil heterogeneity and biogeochemistry is unclear, with most information limited to North America (Taylor and McDaniel, 1998; Lesica and Miles, 2001; Lesica and DeLuca, 2004; Ladenburger et al., 2006). Soil spatial heterogeneity associated with resource islands beneath tamarisk and the effect of tamarisk on the environment is poorly understood, especially in the northern Taklamakan Desert. Although Qong et al. (2002) described the processes of tamarisk mound formation and structure in moving sand dunes in the Taklamakan Desert, the study did not describe the changes in soil chemical properties. The influence of tamarisk on soil salinity, pH, and nutrient availability is largely unknown (Ladenburger et al., 2006), and only a few study have evaluated tamarisk resource islands in the Tarim Basin, China (Yin et al., 2007, 2008). In the present study, we hypothesized that tamarisk plants enriched soil fertility and salinity in multiple environments and that the effects of resource islands were mainly determined by the growth status of tamarisk shrubs.

2. Materials and methods

2.1. Study site

The study site was a tamarisk shrubland in southwestern Luntai County (41°20′–41°40′N, 84°00′–84°20′E, 920–1000 m altitude) in Xinjiang, China (Fig. 1). The site is in an alluvial plain between the Luntai oasis and the Taklamakan Desert. Elevation in the study area declines from north to south. The annual average precipitation is 52 mm and occurs mainly in summer (June–August). Relative humidity is commonly less than 50%, and the mean annual potential evaporation is 2072 mm. The average extreme temperatures are −23 °C in winter (December–February) and 41 °C in summer. Water is the most critical factor limiting plant growth in the area. The vegetation type is temperate desert shrub, and patches of tamarisk dominate the vegetation.

2.2. Sampling methodology

The study was performed in September, 2003. Three 900-m^2 quadrats were randomly selected at approximately 15-km intervals along a transect from the upper to the lower region of the alluvial plain (Table 1 and Figs. 1 and 2). In each quadrat, three living tamarisk plants with similar canopy size, height, and stem number were selected. The distance between the three shrubs was approximately 5–10 m. Soil samples were collected along horizontal transects on four radii surrounding the base of each tamarisk stem. The radii were near the root zone (R), beneath the canopy (C), on the edge of the tamarisk mounds (M), and on open land outside the mounds (O). Soil samples in each radius were collected according to south–north–west–east directions at four depths (0–5, 5–10, 10–30, and 30–100 cm) at the upper and middle alluvial plain sites. Because the soil was too hard to sample with our auger at the 30–100 cm depth at the lower alluvial plain site, samples were collected from only three depths (0–5, 5–10, and 10–30 cm). The soil samples were homogenized and stored in sealed plastic bags. The distance from the edge of each tamarisk mound to open land was about 2 m. The mounds beneath the tamarisk shrubs are distinct from the open land, with a darker soil color compared with the open land (Fig. 3a–c).

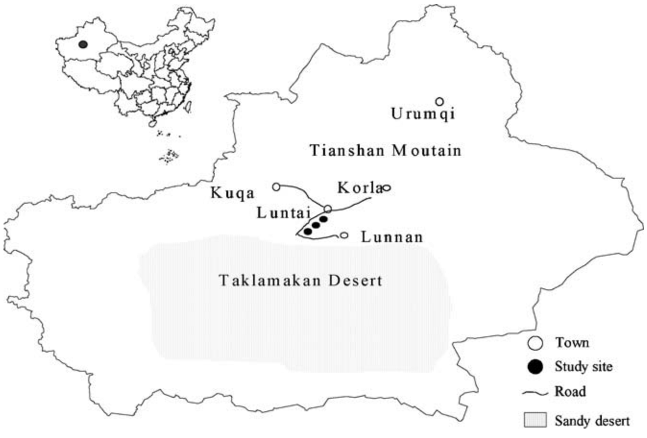


Fig. 1. Position of study area in Xinjiang Autonomous Region, China.

Table 1
Plant community composition and estimated percent cover of individual species, fresh weight (FW), canopy volume, and live and dead plant densities of Tamarix, soil characteristics in three landscape locations: upper, middle and lower of alluvial plain cover.

	Alluvial plain position		
	Upper	Middle	Lower
FW (kg/plant)	26.4	45.4	6.0
Canopy volume (m^3)	13.1	13.1	2.2
Density (plant/ha)			
Living	44	44	69
Dead	55	11	336
Mortality (%)	56	20	83
Cover of different species (%)			
Tamarix spp.	7.4	6.1	1.8
Halostachys caspica	2–3	0–1	0
Phramites australis	0–1	0	0
Alhagi sparsifolia	0	0–1	0
Soil type	Orthic solonchak	Orthic solonchak	Residual solonchak
Bulk soil moisture contents (0–30 cm depth)	14.2 a	16.4 a	1.7 b
Bulk soil EC (0–30 cm depth)	18.9 a	19.8 a	6.3 b
Bulk soil pH (0–30 cm depth)	8.2 a	7.8 b	7.8 b
Soil texture	Loam	Loam	Silt clay loam
Elevation (m)	980	943	920
Longitude	84°18′89.2″	84°00′46.7″	84°03′80.8″
Latitude	41°42′82.5″	41°43′63.3″	41°29′56.3″

2.3. Laboratory analysis

Soil samples were air-dried and sieved through a 2-mm screen for the analysis of 1 M ammonium acetate extractable potassium (K). The content of extractable K was determined with a flame photometer (Model 2655-00 Digital Flame Analyzer, Cole-Parmer Instrument Company, Chicago, IL). Available phosphorus (P) was determined using bicarbonate extraction (Olsen and Sommers, 1982) with a spectrophotometer (UV-120-02 Spectrophotometer, Shimadzu, Kyoto, Japan). Soil organic matter (SOM) was analyzed by the Walkley–Black dichromate wet digestion method (Nelson and Sommers, 1996). Soil electric conductivity (EC) was determined with a conductance instrument (EC 215 conductance instrument, Hanna Co., Italy) using a 1:5 soil/water ratio. Soil pH was determined using a pH meter (PH-2C pH meter, Shanghai Lida Apparatus Manufactory, China) with 1:5 soil/water ratio (Bao,

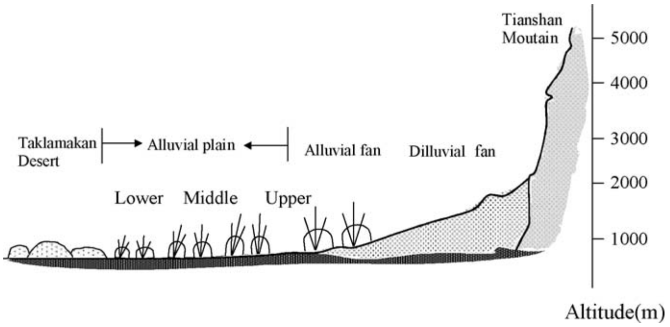


Fig. 2. Sketch map of study area (modified from Qong et al., 2002).

2000). Soil Na^+ and K^+ was extracted using a 1:5 soil/water ratio and analyzed with a flame photometer (Model 2655-00 Digital Flame Analyzer, Cole-Parmer Instrument Company, Chicago, IL). Soil moisture content was determined by an oven-dried method (Bao, 2000). The composition of the plant communities was surveyed in the field and, along with the soil properties, is shown in Table 1. Biomass of tamarisk plants was determined by harvesting aboveground shrub samples and determining their fresh weight (FW).

2.4. Calculations

To describe the inter-site variations in soil fertility within the mounds (R, C and M) and to compared the differences in soil fertility between the soil beneath the canopy and the soil in the open land (O), the enrichment ratio (E) was defined as the mean soil parameter value within the mound (i.e., $[(R + C)/2]$) divided by the mean soil parameter value of the open land. E values above 1 signify greater soil fertility below tamarisk shrubs than in the open land (Wezel et al., 2000). Average values of soil salinity and nutrients in samples from 0 to 5, 5 to 10 and 10 to 30 cm depths were used to calculate E for surface soil (0–30 cm).

2.5. Statistical analysis

Data were subjected to factorial analysis of variance using a one-way ANOVA model in the SAS v. 8.1 software packageA least significant difference test at $p = 0.05$ was used to compare means between the three microsites or between the four sampling locations at each site.

3. Results

3.1. Growth and cover of tamarisk plants

Although tamarisk density was highest at the lower alluvial plain region than at the upper or middle regions, the mean tamarisk FW biomass was greater at the upper or middle regions compared to the lower alluvial plain region (Table 1). Tamarisk mortality was much higher at the lower alluvial plain region than at the upper and middle regions. The average tamarisk canopy cover volumes were 13.1 m^3 per plant for the upper and middle regions but only 2.2 m^3 for the lower alluvial plain region.

Tamarisk was the dominant plant at all three alluvial plain positions (Table 1), and the species composition at each location was simple. At the upper and middle alluvial plain regions, *Halostachys caspica* (small shrub), *Phragmites australis* (perennial herbage), and *Alhagi sparsifolia* (perennial herbage) grew in addition to tamarisk (*Tamarix* spp.) but were less frequent. At the lower alluvial plain region, the whole plant community was becoming sparse and giving way to a sandy, desert-like landscape. Therefore, only small tamarisk shrubs were present at the lower region. Tamarisk canopy cover and plant community composition at the three sites are shown in Table 1, and photographs of tamarisk shrubs at the upper, middle, and lower alluvial plain regions are shown in Fig. 3a–c.

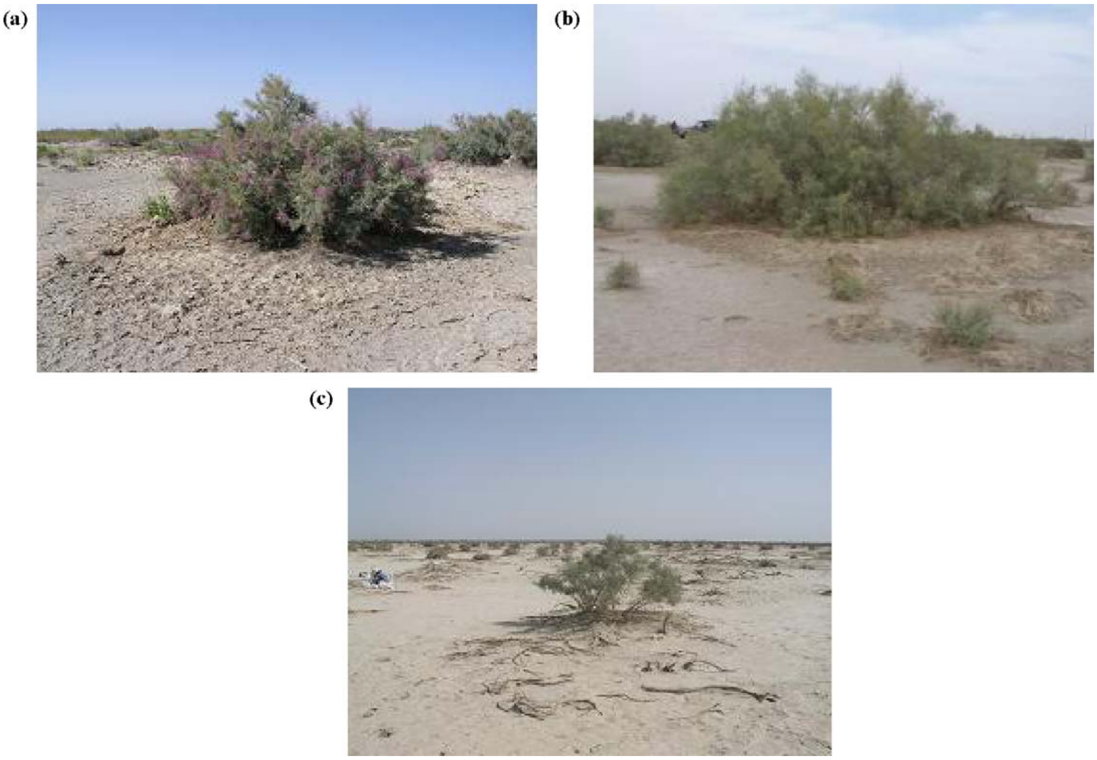


Fig. 3. Tamarisk mound at each landscape location (a) upper alluvial plain, (b) middle alluvial plain, (c) lower alluvial plain.

Table 2
Comparison of SOM (soil organic matter) (g/kg), available soil P (mg/kg), and extractable soil K contents (mg/kg) among the four sampling sites in relation to tamarisk shrubs: root zone (R), canopy (C), edge of mound (*E*), and open land (O) in tamarisk communities in three alluvial plain locations; 'upper', 'middle' and 'lower' represent the communities in these topographic positions. Within a row, means followed by the same capital letter are not significantly different at $p = 0.05$ by LSD; means with same letter on the same line do not differ at $p = 0.05$ by LSD.

	R	C	M	O	*E*
SOM (g/kg)					
0–30 cm					
Upper	24.7 aA	22.3 aA	9.8 bA	4.8 cA	5.2 A
Middle	25.5 aA	15.3 bAB	4.3 cB	3.7 dA	5.7 A
Lower	10.6 aA	8.9 aB	5.7 bB	5.4 bA	1.8 A
30–100 cm					
Upper	17.4 aA	11.7 abA	5.8 bcA	3.8 cA	3.9 A
Middle	8.1 aA	6.3 aA	2.9 aA	3.4 aA	1.9 A
Lower	–	–	–	–	
Available soil P (mg/kg)					
0–30 cm					
Upper	17.1 aA	15.7 aA	12.4 abA	8.6 cA	2.0 A
Middle	20.9 aA	12.2 bA	6.3 cB	7.1 cA	2.8 A
Lower	17.7 aA	16.0 aA	8.9 bAB	5.1 cA	3.9 A
30–100 cm					
Upper	13.8 aA	13.5 aA	10.1 aA	9.6 aA	1.5 A
Middle	18.2 aA	8.1 aA	4.8 aA	12.6 aA	2.0 A
Lower	–	–	–	–	
Extractable soil K (mg/kg)					
0–30 cm					
Upper	2141 aA	1526 bA	696 cA	264 dAB	6.9 A
Middle	797 aB	627 bB	315 cB	274 cA	2.6 B
Lower	877 aB	830 aB	391 bB	187 cB	4.6 AB
30–100 cm					
Upper	669 aA	579 abA	495 bcA	355 cA	1.8 A
Middle	333 aB	305 abB	249 bA	247 bB	1.3 A
Lower	–	–	–	–	

3.2. *Characteristics of soil fertility within and around the tamarisk mounds*

The color of the surface soil under tamarisk mounds was darker than the surface soil in the open land (see Fig. 3a–c), suggesting a difference in soil characteristics between these two environments. SOM, available P, and extractable K were greater within the canopy than outside at the upper, middle, and lower regions. At the upper alluvial plain region, SOM near the root zone (R) and beneath the canopy (C) was significantly greater than outside the canopy (O) at all sampling depths. In contrast, significant differences in SOM between the root zone (R) and open land (O) were only observed in samples from 0 to 30 cm depths at the middle and lower regions of the alluvial plain (Table 2). SOM beneath the canopy (C) was significantly greater at the 0–30 cm depth in the upper, middle, and lower regions as compared to open land (O) (Table 2). This indicates that organic carbon accumulated throughout the soil profile at the upper region and in the surface soil beneath the tamarisk canopy in all regions. Compared to open land (O), available soil P in the surface layers (0–30 cm) near the root zone (R) and beneath the tamarisk canopy (C) was significantly greater at all regions of the alluvial plain. Extractable soil K near the root zone (R) was significantly greater compared to the open land (O) at both soil depths at the upper and middle regions and at the 0–30 cm depth at the lower region. Extractable soil K beneath the canopy (C) was significantly greater compared to the open land (O) at both soil depths at the upper region and at the 0–30 cm depth at the middle and lower alluvial plain regions. Thus soil P and K were markedly concentrated in the surface soil layers beneath the tamarisk canopies compared to open land at all three locations.

Table 3
Comparison of EC (ds/m), pH (l/c), and soil Na^+ contents (mg/kg), soil K^+ contents (mg/kg) among the four sampling sites in relation to tamarisk shrubs: root zone (R), canopy (C), edge of mound (*E*), and open land (O) in tamarisk communities in three alluvial plain locations; 'upper', 'middle' and 'lower' represent the communities in these topographic positions. Within a row, means followed by the same capital letter are not significantly different at $p = 0.05$ by LSD; means with same letter on the same line do not differ at $p = 0.05$ by LSD.

	R	C	M	O	*E*
$EC_{1:5}$ (dS/m)					
0–30 cm					
Upper	29.0 abA	31.6 aA	36.5 aA	23.2 bA	1.3 B
Middle	43.8 aA	41.7 aA	23.7 bB	19.4 bA	2.2 A
Lower	9.8 abB	11.2 aB	11.1 aC	7.4 bB	1.4 B
30–100 cm					
Upper	13.4 bA	18.4 aA	15.6 abA	14.8 bA	1.2 A
Middle	15.8 aA	17.0 aA	14.1 aA	15.4 aA	1.1 A
Lower					
$pH_{1:5}$ (l/c)					
0–30 cm					
Upper	8.8 aA	8.9 aA	8.5 bA	8.3 cA	1.0 A
Middle	8.2 aB	8.2 aA	7.8 bB	7.8 bA	1.0 A
Lower	8.4 aAB	8.1 abA	8.0 bAB	7.7 bA	1.0 A
30–100 cm					
Upper	8.5 aA	8.5 aA	8.2 aA	8.2 aA	1.0 A
Middle	8.0 aB	7.8 bA	7.7 bB	7.7 bB	1.0 A
Lower					
Na^+ (g/kg)					
0–30 cm					
Upper	34.5 aAB	55.9 aA	73.6 aA	61.9 aA	1.1 B
Middle	63.6 aA	67.8 aA	35.7abAB	29.6 bA	2.3 A
Lower	11.2 abB	14.9 aB	13.3 aB	6.8 bA	1.9 AB
30–100 cm					
Upper	42.4 aA	48.0 aA	45.8 aA	44.0 aA	1.0 A
Middle	14.4 cA	26.2 aA	20.1 bA	19.3 bA	1.1 A
Lower					
K^+ (g/kg)					
0–30 cm					
Upper	1.2 aA	1.0 aA	0.5 bA	0.1 cA	10.5 A
Middle	0.7 aB	0.6 aB	0.3 bB	0.2 bA	3.2 A
Lower	0.7 aB	0.7 aAB	0.2 bB	0.1 cA	5.6 A
30–100 cm					
Upper	0.3 abA	0.4 aA	0.2 abA	0.2 bA	1.9 A
Middle	0.3 aA	0.2 aA	0.2 aA	0.2 aA	1.5 A
Lower	–	–	–	–	–

3.3. *Soil salinity characteristics within and around the tamarisk mounds*

Soil salinity differed beneath and outside tamarisk mounds. At the upper alluvial plain region, EC under the canopy (C) was significantly greater compared to outside the canopy (O) at both sampling depths (Table 3). This was also true for the 0–30 cm depth at the middle and lower alluvial plain regions. Compared to the open land (O), soil pH in the surface layers (0–30 cm) near the root zone (R) and beneath the canopy (C) were significantly greater at the upper, middle, and lower alluvial plain regions. At a depth of 30–100 cm, significantly higher soil pH was found near the root zone (R) compared to all other positions around tamarisk plants. At the upper region, there were no significant differences in soil Na^+ among the root zone (R), the canopy (C), the edge of mounds (M), or the open land (O) at both soil depths. At the middle region, soil Na^+ near the root zone (R) was significantly greater than in the open land at the 0–30 cm depths, while Na^+ beneath the tamarisk canopy (C) was significantly greater at both soil depths as compared to open land (O). Soil Na^+ beneath the canopy (C) was significantly greater than in the open land (O) at the lower alluvial plain region at 0–30 cm depth. Soil K^+ was significantly higher near the root zone (R) and under the canopy (C) compared to the open land (O) at the depth of 0–30 cm at all three locations in the alluvial plain. At the 30–100 cm depth, significantly higher soil K^+ content was only found beneath the tamarisk canopy (C) compared to open land (O) at the upper alluvial plain region.

3.4. Enrichment ratios at the three sampled locations

SOM near the root zone (R) and under the tamarisk canopy (C) in the upper alluvial plain region was similar to that of middle region, and both were higher than the SOM of the lower region. SOM in the open land (O) in the upper alluvial plain region was similar to that of the other two locations. The enrichment ratios (E) for these samples are presented in Table 2. The trend in SOM enrichment ratios from each location was similar to that of SOM near the root zone (R) and under the tamarisk canopy (C) for the 0–30 cm depth. This is consistent with the growth pattern of tamarisk plants in the three regions of the alluvial plain. These results suggest that the tamarisk effects on SOM were determined by growth patterns. Available soil P near the root zone (R) and under the tamarisk canopy (C) was similar at the three sites. In open land (O), available soil P decreased from the upper to lower regions. The enrichment ratio (E) for available soil P was highest in the lower region and lowest in upper region (Table 2). These results suggest that the available soil P beneath tamarisk canopy was not sensitive to variations in tamarisk growth. Extractable soil K near the root zone (R) and under the tamarisk canopy (C) was significantly greater in the upper alluvial plain region compared to the other two locations. The lowest extractable soil K near the root zone (R) and under the tamarisk canopy (C) was observed in the middle region. The extractable soil K in the open land was highest in the middle region and lowest in lower region. At sample depths of 0–30 cm, the enrichment ratio for extractable soil K was highest in the upper region and lowest in middle alluvial plain region. These results indicate that the variation in extractable soil K was not directly related to the growth status of tamarisk. Nutrient enrichment was greater in surface soils (0–30 cm) compared to deeper soils (30–100 cm), indicating that the enrichment of different nutrients induced by tamarisk mainly occurred in the topsoil layer beneath the tamarisk canopy.

Trends in soil EC were similar to trends in soil Na^+ near the root zone (R), beneath the canopy (C), and in open land (O) for samples from 0 to 30 cm depth at all three sites. Soil EC and Na^+ near the root zone (R) and beneath the canopy (C) were highest in the middle region and lowest in lower region. However, soil EC and Na^+ in the open land (O) were highest in the upper region, while lowest in lower region. These results suggest that the effects of tamarisk shrub on soil salinity and Na^+ increased from the upper region to the middle region but decreased from the middle region to the lower region. In contrast, soil salinity and Na^+ in the open land decreased from the upper to lower region. The salinity enrichment ratios (E) are presented in Table 3. The enrichment ratios for soil salinity and Na^+ in the middle region were significantly higher than the enrichment ratios for the other two locations. For the upper and lower regions, no significant difference in enrichment ratios of soil salinity and Na^+ was observed, similar to the trends for SOM. This indicated that enrichment of soil salinity and Na^+ were directly related to the growth of tamarisk. Soil pH near the root zone (R), beneath the canopy (C), and in the open land (O) were highest in the upper region and lowest in middle region. Similar results were observed in soil K^+ near the root zone (R) and under the shrub canopy (C) at all three locations. For open land, however, soil K^+ was highest in the middle region, but lower in the upper and lower regions. No obvious trends in pH enrichment ratios at the three locations. Interestingly, soil K^+ enrichment ratios were different than enrichment ratios for soil salinity and Na^+ in that they were highest in the upper region and lowest in the middle region. These results indicate that the variation in some salinity components (e.g., pH, K^+) was not correlated to tamarisk growth. Enrichment of soil salinity, Na^+, and K^+ was greater in surface soil (0–30 cm) compared to the 30–100 cm depth. These results suggest that the enriching influence of tamarisk on soil salinity was mainly limited in surface soil.

3.5. Relationship between SOM, salinity, enrichment ratio, and shoot biomass

SOM and the enrichment ratios for SOM at the 0–30 cm depths were positively correlated with shrub shoot fresh biomass (Fig. 4). This indicates that the accumulation of SOM in the topsoil was related to the growth pattern of the tamarisk shrubs. However, no correlation was observed between shrub shoot fresh biomass and soil available P or the soil available P enrichment ratios (Fig. 5). Soil extractable K and the soil extractable K enrichment ratios were not related to shrub shoot fresh biomass (Fig. 6). These results suggest that the accumulation of soil available P and soil extractable K were not directly determined by growth of tamarisk plants.

EC and the EC enrichment ratios at 0–30 cm depths were also positively correlated with shrub shoot fresh biomass (Fig. 7). These results illustrate that the accumulation of salinity in the topsoil was significantly affected by the growth pattern of the tamarisk

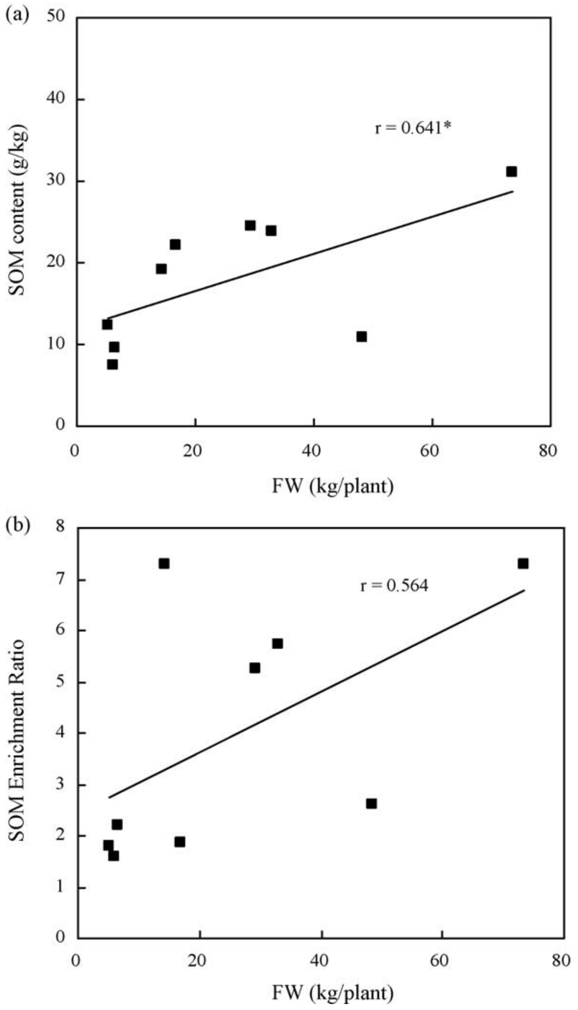


Fig. 4. Relationship between tamarisk shoot fresh weight (FW) and SOM contents (a), SOM enrichment ratio (b) within tamarisk mounds at 0–30 cm depths. r are regression parameters at 0–30 cm depth, (*), Significant at $p = 0.05$; $n = 9$.

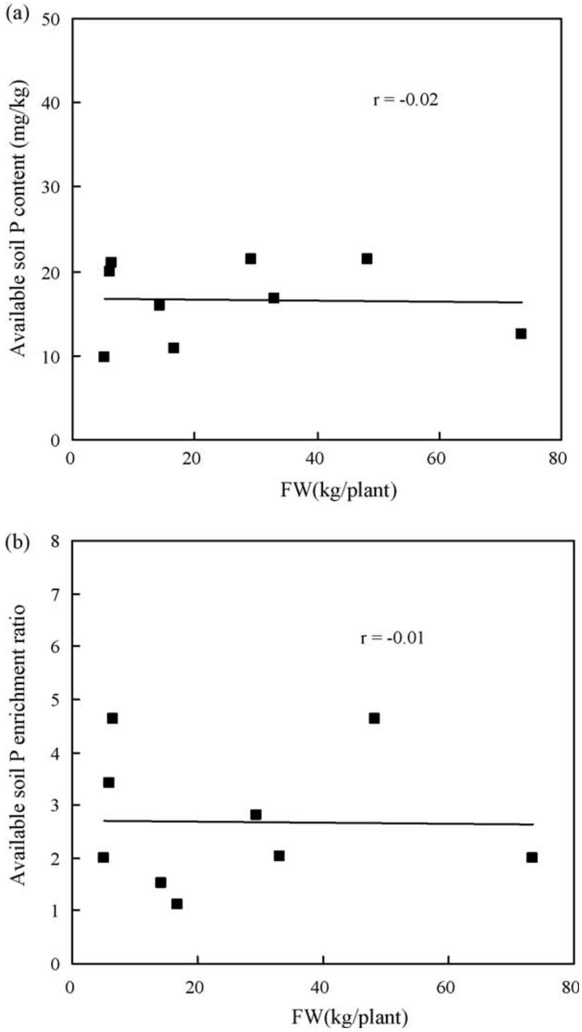


Fig. 5. Relationship between tamarisk shoot fresh weight (FW) and available soil P contents (a), available soil P enrichment ratio (b) within tamarisk mounds at 0–30 cm depths. *r* are regression parameters at 0–30 cm depth, (*), Significant at $p = 0.05$; $n = 9$.

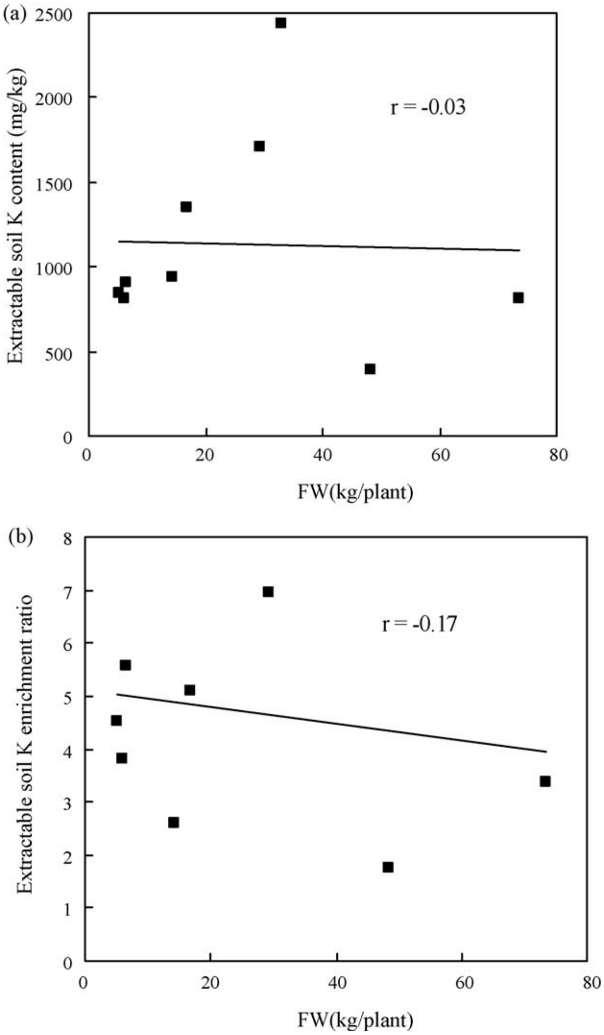


Fig. 6. Relationship between tamarisk shoot fresh weight (FW) and extractable soil K contents (a), extractable soil K enrichment ratio (b) within tamarisk mounds at 0–30 cm depths. *r* are regression parameters at 0–30 cm depth, (*), Significant at $p = 0.05$; $n = 9$.

shrubs. Similar results were not observed between soil K^+ and shrub shoot fresh biomass (Fig. 8). A significant correlation was observed between shrub shoot fresh biomass and soil Na^+ at 0–30 cm depths (Fig. 9a), but no such correlation existed between soil Na^+ enrichment ratios and shrub shoot fresh biomass (Fig. 9b). These results indicate that soil Na^+ contents beneath the canopy were directly influenced by the growth of tamarisk as well as by soil EC.

4. Discussion

Desert soil fertility is generally poor, and spatial heterogeneity of soil resources is a common feature of desert soils (Midgley and Musil, 1990; Schlesinger et al., 1990, 1999). Our results show that there were different resource (including fertility and salinity) islands beneath the canopy of *Tamarix* spp. (tamarisk shrubs) in various locations in the northern Taklamakan Desert. Such spatial heterogeneity of soil resources resulted from tamarisk enhancing soil fertility and salinity. The formation of resource islands in arid regions is a result of complex interactions between biotic and abiotic processes, including interactions between the plants, soil biota, the atmosphere, and biogeochemical cycling processes (Garner and Steinberger, 1989). Rainfall is one of the most important abiotic factors in the development of resource islands and the build-up of mounds beneath desert shrubs (Schlesinger et al., 1999; Wainwright et al., 1999). Nevertheless, it is difficult to link rainfall to the formation of tamarisk resource islands in the Taklamakan Desert because the annual precipitation is only 52 mm (Su, 1991). Flood and wind effects likely have more influence than rainfall on the development of resource islands. In our study area, runoff due to flooding and wind speeds reached 787 m^3/s and 23 m/s, respectively (Su, 1991). We observed an obvious mound beneath each tamarisk canopy and clear signs of water erosion in the open land, especially in the middle alluvial plain region (Fig. 3a and b). Thus, flooding may enhance the effect of resource islands beneath tamarisk shrubs by increasing interspaced runoff erosion. Other studies have also shown that isolated shrubs give rise to changes in topsoil properties (i.e., increased organic matter content and aggregate stability beneath shrubs), mainly because of alteration of erosion/sedimentation processes by aboveground plant structures (Bochet et al., 1999). In the lower alluvial plain region, the plant community is clearly degenerating and seemed to be strongly influenced by wind erosion (Fig. 3c). The lowest observed SOM enrichment at this location might be due to erosion of soil fertility and the poor growth status of tamarisk. This is consistent with previous findings

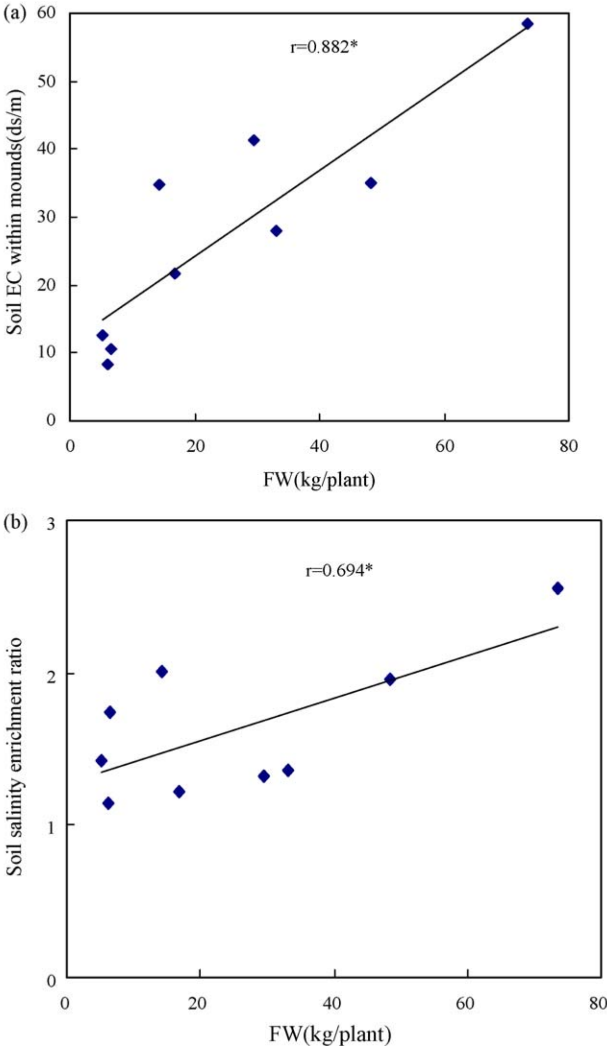


Fig. 7. Relationship between tamarisk shoot fresh weight (FW) and soil salinity contents (a), soil salinity enrichment ratio (b) within tamarisk mounds at 0–30 cm depths. *r* are regression parameters at 0–30 cm depth, (*), Significant at $p = 0.05$; $n = 9$.

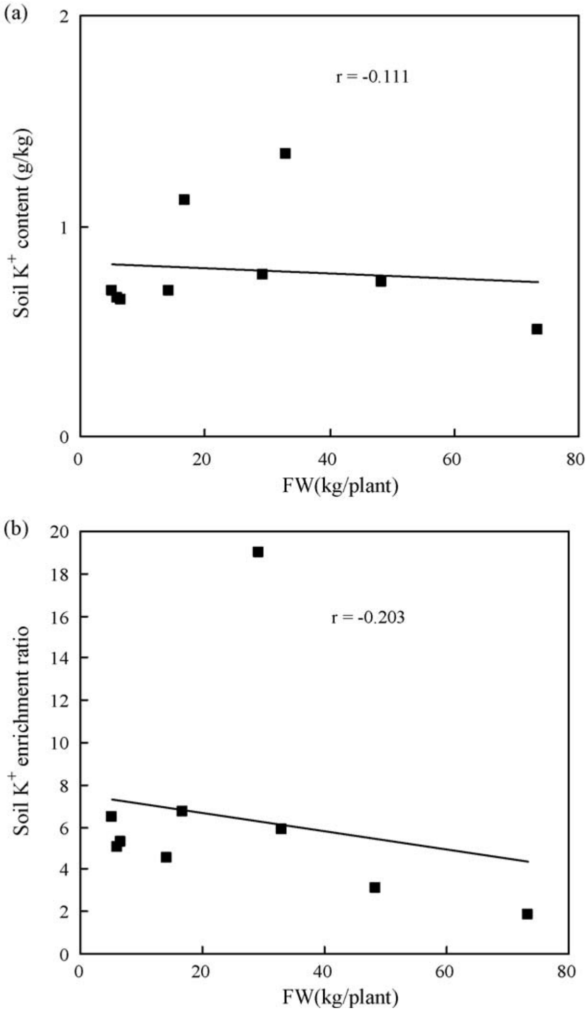


Fig. 8. Relationship between tamarisk shoot fresh weight (FW) and soil K$^+$ contents (a), soil K$^+$ enrichment ratio (b) within tamarisk mounds at 0–30 cm depths. *r* are regression parameters at 0–30 cm depth, (*), Significant at $p = 0.05$; $n = 9$.

that suggest wind erosion may lead to the destruction of fertility islands by burial and/or abrasion of shrubs (Okin et al., 2001).

Burke et al. (1998) suggested that resource islands form when plant roots scavenge nutrients and salinity in interspaces. A study of the semiarid Horqin sandy land in China also suggested that the growth of roots favors the development of resource islands by increasing rhizodeposition (Su et al., 2004). Therefore, the formation of islands beneath tamarisk canopies may be attributed, in part, to rhizosphere processes. Rhizosphere processes also influence the overall growth of tamarisk plants. Therefore, different plant growth patterns likely resulted in different SOM enrichments within the tamarisk resource islands at the three sites (Fig. 4). Other studies have also indicated that the spatial distribution of soil organic carbon in rangelands is highly correlated with vegetation patterns and plant community dynamics (Schlesinger et al., 1990, 1996; Schlesinger and Pilmanis, 1998; Smith et al., 1994). Thus, rhizosphere processes were important drivers in the distribution of soil nutrients in relation to tamarisk shrubs.

Recent studies have indicated that tamarisk plants take up water and nutrients from groundwater in the southern Taklamakan Desert (Arndt et al., 2004; Gries et al., 2003), and the root systems that access groundwater play important roles in water and nutrient uptake through hydraulic lift (Arndt et al., 2004). Therefore, groundwater availability and depth may directly influence the growth status of tamarisk and the effects of tamarisk rhizhospheres. Song (2000) defined ecological groundwater tables, including the concept of an optimal groundwater table for growth of riparian vegetation (e.g., tamarisk, Euphrates Poplar). Growth of tamarisk will be best above an optimum groundwater table compared to other groundwater tables because of the availability of water and decreased salinity. Therefore, the contribution of tamarisk on soil fertility was highest at the optimum groundwater table because of the effect on net primary production (NPP). Soil fertility heterogeneity was highest at the optimum groundwater table where tamarisk growth was best. In our study, the SOM enrichment ratio was highest in the middle alluvial plain region, presumably due to superior growth of tamarisk compared to the other two locations. This likely resulted from an optimum groundwater table at the middle region, which corresponds to the soil salinity and water content in the topsoil at the three regions. Concentration of some nutrients and elements (e.g., soil available P, extractable K) did not correlate to tamarisk growth. Nevertheless, available K in the topsoil underneath the canopy at the upper alluvial plain region (2300 mg/kg) was significantly greater than available K in the open land (250 mg/kg) (Table 2). The former was extremely high compared to farmland soil, which typically has soil available K of 119–193 mg/kg (Zhang et al., 2000).

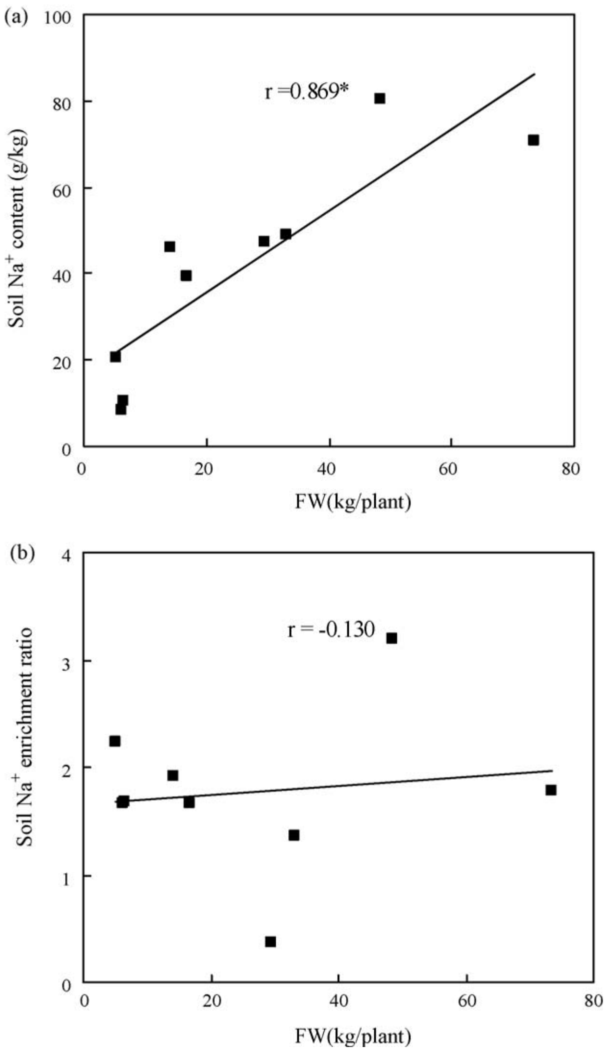


Fig. 9. Relationship between tamarisk shoot fresh weight (FW) and soil Na^+ contents (a), soil Na^+ enrichment ratio (b) within tamarisk mounds at 0–30 cm depths. *r* are regression parameters at 0–30 cm depth, (*), Significant at $p = 0.05$; $n = 9$.

The enrichment of soil available K was approximately 4–8 times that of open land in all three locations (Table 2). These data indicate that soil available K underneath tamarisk canopies was strongly affected by tamarisk growth. In Mali, soil fertility enrichments are mainly attributed to the leaves of the shrubs (Kassogué et al., 1996). The mechanism of soil nutrients enrichment in tamarisk mounds appear to be also related to foliars and litterfall, and therefore reasons given for the harmful aspects of tamarisk need to be moderated (Glenn and Nagler, 2005).

Variations in soil EC, the EC enrichment ratio, and soil Na^+ within tamarisk resource islands at the sampled sites were also consistent with the growth status of tamarisk (Fig. 7, Fig. 8a). These results suggest that soil salinity within tamarisk resource islands is influenced by the growth status of tamarisk as well as soil fertility. Tamarisk adds salt to the soil through its foliar litter, which is high in salt content (DiTomosa, 1998; Smith et al., 1998). Tamarisk plants absorb salts from deeper soil layers and transport it to the leaves through the plant. The salts are eventually deposited on the soil surface beneath the shrub canopy after foliar drop or following rainfall events (Kerpez and Smith, 1987). Other studies, however, indicate that salt is transported to surface soils by capillary action instead of through leaf processes (Anderson, 1998; Tomar et al., 2003). This process favors tamarisk growth and excludes mesophytes (Anderson, 1998). Salt accumulation to alarming levels was observed in the soil as a consequence of irrigating with saline water (Tomar et al., 2003). Removing tamarisk, therefore, might have little effect on total soil salt levels (Anderson, 1998). In Xinjiang arid zones, tamarisk is considered a key species in saline soil melioration and revegetation efforts in the southern Taklamakan Desert (Liu, 1996). The results of their studies are contrary to ours (Table 2). Our inability to distinguish salinity resulting from tamarisk litterfall from salinity result from capillary action beneath the shrub may account for the discrepancies among the studies. Salinity accumulation in surface soils by capillary action is an abiotic process. In general, such a process can be inhibited by tamarisk because of shade effects. Our study suggested that soil water content beneath tamarisk canopies is significantly lower than outside canopies (Yin et al., 2007). These results suggest that capillary action was less significant in tamarisk mounds compared to open land, presumably due to shade effects. Therefore, salinity accumulation within resource islands resulting from capillary action should be lower than in interspaces. Our results, however, suggest that the salinity accumulation was higher in tamarisk mounds compared to interspaces at all three locations (Table 3). Therefore, the increase in salinity in tamarisk mounds compared to open land was attributed to litterfall of tamarisk. When analyzing salinity islands, the effects of tamarisk litterfall production versus capillary action in open land should be included. In this study, litter production was determined by the growth of tamarisk, which could be related to the ecological groundwater table. At the optimum groundwater table, tamarisk growth will be greater when compared to other locations because of the positive effects on the plant rhizosphere. Similarly, the effect of capillary action was moderate, which allowed sufficient water for the plant but transported less salinity to the surface soil. Therefore, the enrichment ratio of soil salinity and Na^+ was highest in middle alluvial plain region because of the optimum groundwater table (Table 3).

5. Summary

Tamarisk enriched both soil fertility and salinity in the northern Taklamakan Desert. The enrichment process was complex and depended on many variables. Increases in salinity were attributed to deposition of salts in tamarisk leaf litter. The growth of tamarisk in relation to the depth to the groundwater table was also an important factor in determining the development of canopy resource islands. Based on these data, a proposal model of soil resource heterogeneity among different groundwater table depths is presented in Fig. 10. This model indicates that soil resource heterogeneity increases when moving from shallow groundwater tables to deeper groundwater

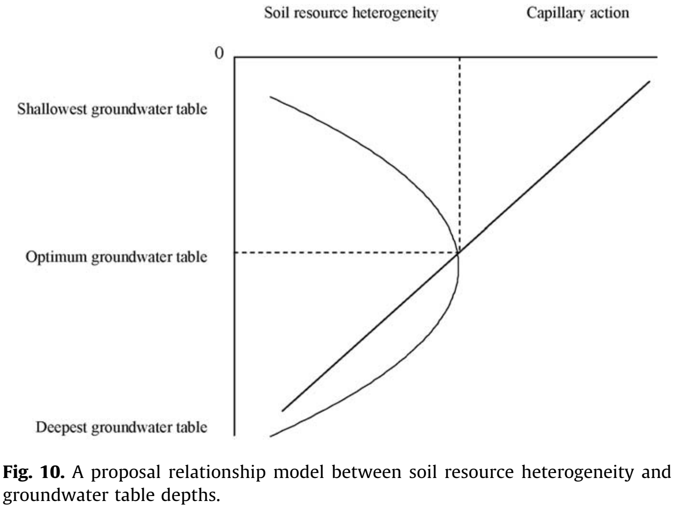


Fig. 10. A proposal relationship model between soil resource heterogeneity and groundwater table depths.

tables and that tamarisk plants thrive at the optimum groundwater table before decreasing in abundance at a deeper groundwater table. Therefore, caution is warranted in using tamarisk as restoration plants, and different tamarisk shrub management strategies are needed for different groundwater table depths. For example, control of the tamarisk plant density is necessary to develop saline agriculture and for revegetation projects in the Xinjiang arid zone.

Acknowledgements

This study was funded by the Natural Science Foundation of China (Grant No. 40701081), the innovative group grant of NSFC (No. 30821003) and Western PhD Programs of the Chinese Academy of Science, China. We would like to thank Professor Zili Fan for his valuable help in identification of soil types in the field. We are thankful to Dr. Peter Christie for his critical reading and revision of the manuscript.

References

Anderson, B., 1998. The case for saltcedar. Restor. Manag. Notes 16, 130–134.

Arndt, S.K., Kahmen, A., Arampatsis, C., Popp, M., Adams, M., 2004. Nitrogen fixation and metabolism by groundwater-dependent perennial plants in a hyperarid desert. Oecologia 141, 385–394.

Bao, S.D., 2000. Analysis Method of Soil and Agricultural Chemicals. Chinese Agricultural Science and Technology Publishing House, Beijing, p. 481.

Bochet, E., Rubio, J.L., Poesen, J., 1999. Modified topsoil islands within patchy Mediterranean vegetation in SE Spain. Catena 38, 23–44.

Brotherson, J.D., Field, D., 1987. Tamarix: impacts of a successful weed. Rangelands 9, 110–112.

Burke, I.C., Lauenrth, W., Vinton, M.A., 1998. Plant-soil interactions in temperate grasslands. Biogeochemistry 42, 121–143.

Busch, D.E., Smith, S.D., 1995. Mechanisms associated with decline of woody species in riparian ecosystems of the southwestern U.S. Ecol. Monogr. 65, 347–370.

Di Tomaso, J.M., 1998. Impact, biology, and ecology of saltcedar (*Tamarix* spp.) in the southwestern United States. Weed Technol. 12, 326–336.

Ellis, L.M., 1995. Bird use of saltcedar and cottonwood vegetation in the Middle Rio-Grande Valley of New-Mexico, USA. J. Arid Environ. 30, 339–349.

Garner, W., Steinberger, Y., 1989. A proposed mechanism for the formation of 'fertile islands' in the desert ecosystem. J. Arid Environ. 16, 257–262.

Glenn, E.P., Nagler, P.L., 2005. Comparative ecophysiology of *Tamarix ramosissima* and native trees in western U.S. riparian zones. J. Arid Environ. 61, 419–446.

Gries, D., Zeng, F., Foetzki, A., Arndt, S.K., Bruelheide, H.R., Thomas, F.M., Zhang, X., Runge, M., 2003. Growth and water relations of *Tamarix ramosissima* and *Populus euphratica* on Taklamakan desert dunes in relation to depth to a permanent water table. Plant Cell Environ. 26, 725–736.

Grubb, R.T., Sheley, R.L., Carlstrom, R.D., 1997. Saltcedar (tamarisk). Montana State University Extension Service MT9710, Bozeman.

Kassogué, A., Momota, M., Sagara, J., Schutgens, F., 1996. A measure for every site: traditional SWC techniques on the Dogon Plateau, Mali. In: Reij, C., Scoones, I., Toulmin, C. (Eds.), Sustaining the Soil. Indigenous Soil and water Conservation in Africa. Earthscan Publications, London, 260 pp, pp. 69–79.

Kerpez, T.A., Smith, N.S., 1987. Saltcedar control for wildlife habitat improvement in the southwestern United States. U.S. Fish and Wildlife Serv. Resource Pub. 169., Washington, DC, p. 16.

Ladenburger, C.G., Hild, A.L., Kazmer, D.J., Munn, L.C., 2006. Soil salinity patterns in Tamarix invasions in the Bighorn Basin, Wyoming, USA. J. Arid Environ. 65 (1), 111–128.

Lesica, P., Miles, S., 2001. Tamarisk growth at the northern margin of its naturalized range in Montana, USA. Wetlands 21 (2), 240–246.

Lesica, P., DeLuca, T.H., 2004. Is tamarisk allelopathic? Plant Soil 267, 357–365.

Liu, M.T., 1996. Tamarix L. and its extending in the desert region of Xinjiang [J]. J. Desert Res. 16 (4), 428–429.

Midgley, G.F., Musil, C.F., 1990. Substrate effects of zoogenic mounds on vegetation composition in the Worcester-Robertson valley, Cape Province. South Africa. J. Bota. 56, 158–166.

Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. In: Sparks, D.L. (Ed.), Methods of Soil Analysis: Part 3 – Chemical Methods, SSSA-Book Series 5, American Society of Agronomy, Madison, WI, pp. 961–1010.

Okin, G.S., Murray, B., Schlesinger, W.H., 2001. Desertification in an Arid Shrubland in the Southwestern United States: Process Modeling and Validation in Land Degradation. In Papers Selected from Contributions to the Sixth meeting of the International Geographical Union's Commission on Land Degradation and Desertification. In: A Conacher (Ed.), Kluwer Academic Publishers, Dordrecht, pp. 53–70.

Olsen, S.R., Sommers, L.E., 1982. Phosphorus. 2nd Eds. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2, No. 9 in Agronomy Series, 2nd Eds., American Society of Agronomy, Soil Science Society of America, Madison, WI, pp. 403–427.

Qong, M., Takamura, H., Hudaberdi, M., 2002. Formation and internal structure of Tamarix shrubs in the Taklamakan Desert. J. Arid Environ. 50, 81–97.

Schlesinger, W.H., Raikes, J.A., Hartley, A.E., Cross, A.F., 1996. On the spatial pattern of soil nutrients in desert ecosystems. Ecology 77, 364–374.

Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrell, W.M., Virginia, R.A., Whitford, G., 1990. Biological feedbacks in global desertification. Science 247, 1043–1048.

Schlesinger, W.H., Abrahams, A.D., Parsons, A.J., Wainwright, J., 1999. Nutrient losses in runoff from grassland and shrubland habitats in southern New Mexico: I. Rainfall simulation experiments. Biogeochemistry 45, 21–34.

Schlesinger, W.H., Pilmanis, A.M., 1998. Plant–soil interactions in deserts. Biogeochemistry 42, 169–187.

Smith, J.L., Halvorson, J.L., Boton Jr., H., 1994. Spatial relationships of soil microbial biomass and C and N mineralization in a semiarid shrub-steppe ecosystem. Soil Biol. Biochem. 26, 1151–1159.

Smith, S., Devitt, D., Sala, A., Cleverly, J., Busch, D., 1998. Water relations of riparian plants from warm desert regions. Wetlands 18, 687–696.

Song, Y.D., 2000. Research on Water Resources of Tarim River, China. Xinjiang People's Press, Urumqi, pp. 51–52 (in Chinese).

Su, H.F., 1991. Annals of Luntai County. Xinhua press, Beijing, pp. 47–57.

Su, Y.Z., Zhao, H.L., Li, Y.L., Cui, J.Y., 2004. Influencing mechanisms of several shrubs on soil chemical properties in semiarid Horqin Sandy Land, China. Arid Land Res. Manage. 18 (3), 251–263.

Taylor, J.P., McDaniel, K.C., 1998. Restoration of saltcedar (Tamarix sp.)-infested alluvial plains on the Bosque del Apache National Wildlife Refuge. Weed Technol. 12 (2), 345–352.

Tomar, O., Minhas, P., Sharma, V., Singh, Y., Gupta, R., 2003. Performance of 31 tree species and soil conditions in a plantation established with saline irrigation. Forest Ecol. Manage. 177, 333–346.

UNEP, 1997. World Atlas of Desertification, 2nd Eds. Arnold, London.

Vitousek, P.M., 1990. Biological invasions and ecosystem processes: towards an integration of population biology and ecosystem studies. Oikos 57, 7–13.

Wainwright, J., Parsons, A.J., Abrahams, A.D., 1999. Rainfall energy under creosotebush. J. Arid Environ. 43, 111–120.

Wezel, A., Rajot, J.L., Herbrig, C., 2000. Influence of shrubs on soil characteristics and their function in Sahelian agro-ecosystems in semi-arid Niger. J. Arid Environ. 44, 383–398.

Yan, H., Wang, C.H., Niu, Z., Zhang, Y.P., 2002. The remote sensing on the origin of East Asia sandy dust and its transportation route. Progressing Geography 21, 90–94 (in Chinese with English abstract).

Yang, X., 2001. The oasis along the Keriya river in the Taklamakan desert, China, and their evolution since the end of the last glaciation. Environ. Geol. 41, 314–320.

Yin, C.H., Feng, Gu., Tian, C.Y., Bai, D.S., Zhang, F.S., 2007. Influence of tamarisk shrub on the distribution of soil salinity and moisture on the edge of Taklamakan desert. China Environ. Sci. 27 (5), 670–675 (in Chinese with English abstract).

Yin, C.H., Feng, Gu., Tian, C.Y., Bai, D.S., Zhang, F.S., 2008. Variations of the fertile island effects beneath tamarisk in northern Taklamakan Desert, northwestern China and its implication to desertification process. J. Beijing Forestry Univ. 30 (1), 52–57 (in Chinese with English abstract).

Zavaleta, E., 2000. The economic value of controlling an invasive shrub. Ambio 29, 462–467.

Zhang, Y., Mao, D.M., Wang, J.L., Fu, M.X., Li, P., 2000. Developing status of balanced fertilization technology of cotton in Xinjiang. Soils Fertilizers (4), 7–10 (in Chinese with English abstract).

Zhu, Z.D., Chen, Z.P., Wu, Z., 1981. Study on the Physiognomy of Taklamakan Desert Induced by Wind and Sand. Science Press, Beijing, pp. 1–34.