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The effects of soil salt crusts on soil evaporation and chemical changes in different ages of Taklimakan Desert Shelterbelts

J.G. Zhang[1], X.W. Xu[2], J.Q. Lei[2], S.Y. Li[2], R.L. Hill[3], Y. Zhao[1*]

[1]*Key Laboratory of Plant Nutrition and the Agri-environment in Northwest China, Ministry of Agriculture, Northwest A&F University, Yangling, Shaanxi 712100, China.* [2]*Xinjiang Institute of Ecology and Geography, Chinese Academy of Science, Urumqi, Xinjiang 830011, China.* [3]*Department of Environmental Science and Technology, University of Maryland, College Park, MD 20742, USA.* [*]*Corresponding author: yzhaosoils@gmail.com*

Abstract

Understanding soil evaporation in reforestation processes in an area of extreme drought is important. We examined the effects of drip-irrigated, high-salinity groundwater on the formation of soil salt crusts and subsequent soil evaporation in the Taklimakan Desert Highway Shelterbelt. Soil evaporation was measured using micro-lysimeters (MLS, 20 cm in length × 10 cm in diameter), and chemical characteristics, including SOM, total salts, ion composition and pH, were analyzed. The results showed that the inhibition efficiency of salt crusts on soil evaporation decreased from the surface to the lower soil layers. Following irrigation, the inhibition efficiency was 33.0% in the shelterbelt, which was much higher than the 13.8% observed for the bare soil. Total salt content and ion contents (Cl^-, Na^+, and SO_4^{2-}) were much higher for the soil salt crusts than for shifting sandy soils, while the contents of other ions (Mg^{2+}, K^+, Ca^{2+}, HCO_3^-, and CO_3^{2-}) were very similar. The total salt content and ion composition of the salt crusts increased during the first 2 years of shelterbelt age, and decreased from 2 to 5 years. With the increasing age of the shelterbelts, the SOM of the salt crusts increased, whereas the total salts and pH decreased. We concluded that the formation of soil salt crusts results in reduced soil evaporation and the soil chemical condition functioned better for growth of the Taklimakan Desert Highway Shelterbelt.

Keywords: Saline groundwater, drip irrigation, soil salt crusts, chemical properties, evaporation, artificial shelterbelt

1. Introduction

Different types of crusts are present on the surfaces of arid and semi-arid soils (Graef and Stahr, 2000) and may be classified as either physical crusts or biological crusts. Soil salt crusts are different from these two classic types of crusts and are generally formed on soils with high concentrations of Na^+, Mg^{2+}, Ca^{2+}, Cl^-, and/or SO_4^{2-} in the soil solution (Goodall *et al*., 2000; Dos Santos *et al*., 2004; Mees and Singer, 2006), and their formation is influenced by soil particle size, ion composition, climate, groundwater levels, and other factors (Ewing *et al*., 2006). Excepted for those natural formations, it also can form in paddy fields with a shallow groundwater table or in arid regions irrigated with saline water (Grünberger *et al*., 2008; Li *et al*., 2007). Soil salt crusts have been shown to restrict wind erosion due to their dense microstructure (Langston and McKenna Neuman, 2005; Maurer *et al*., 2010) and reduce soil evaporation due to increased soil albedo (Fujimaki *et al*., 2003, 2006).

In the Taklimakan Desert of Northwest China, a highway was built through the desert to access oil fields that were developed in 1997. Afterward, the Taklimakan Desert Highway Shelterbelt was constructed in 2003 to limit sand drift onto 436 km of the highway, which was 72 to 78 m wide. The mobile dunes have been successfully stabilized on both sides of the highway for more than 10 years by introducing several water- and salt-tolerant plants. However, as a result of drip-irrigation with high salinity groundwater (2.8-29.7 g L^{-1}) coupled with high evaporative demands, solute ions have accumulated and salt crusts have become widely distributed on soil surfaces in the shelterbelt (Li *et al*., 2007). Because a lower salt content is associated with shelterbelt tree root zones, plants have not demonstrably suffered from salt injury (Li *et al*., 2007; Zhang *et al*., 2008).

The influence of long-term saline water irrigation on soil processes has attracted much attention (Lei *et al*., 2008). Laboratory column experiments have revealed that salt crusts can reduce soil evaporation under constant meteorological conditions (Fujimaki *et al*., 2006). In addition, soil salt crusts may have some influence on the water balance, which is important to understand in order to adopt proper water management strategies. Although a relationship between evaporation and salinization has been reported (Shimojima *et al*., 1996), the influence of soil salt crusts on soil evaporation with saline water irrigation is unknown. In this study, our goals are i) to examine the effects of drip irrigation with high-salinity groundwater and shelterbelt age on the formation of soil salt crusts; ii) to quantify the impacts of salt crusts on soil evaporation under drip irrigation with high-salinity groundwater; and iii) to understand the chemical changes of soil salt crusts after multiple years of irrigation and at different shelterbelt ages.

2. Materials and Methods

2.1. Site description

This study was conducted at the Taklimakan Desert Research Station of the Chinese Academy of Sciences (39º01´N, 83º36´E, 1,100 m a.s.l.; Figure 1). The annual mean air temperature is 12.4 °C, with the lowest monthly mean temperature of -8.1 °C in December and the highest monthly mean temperature of 28.2 °C in July. The area is considered to be extremely arid with an average annual precipitation of 24.6 mm and an annual potential evaporation of 3,639 mm. Sand storms are frequent and intense with sand-shifting winds and are characterized by an average wind speed of 2.5 m s^{-1} and maximum speeds of 20.0 m s^{-1}; these occur more than 130 days annually.

To safeguard the Taklimakan Desert Highway, an artificial shelterbelt ecosystem was established in 1998 and successfully stabilized sand on both sides of the highway. The plant species within the shelterbelt are mainly highly stress-resistant shrubs with excellent windbreak and sand fixation properties, such as *Calligonum* spp., *Tamarix* spp., and *Haloxylon* spp.. The plants are drip-irrigated with high-salinity groundwater, therefore, soil salt crusts are easily formed and widely distributed in the artificial shelterbelt (Zhang *et al*., 2008).

In the study area, the natural vegetation is extremely sparse except for a few drought-resistant shrubs, such as Tamarix ramosissima and Calligonum *leucocladum*, growing in the inter-dune areas. The coverage is so low that the ground is composed mainly of mobile dunes and large complex dune chains. The soils are mainly nutrient-poor, shifting aeolian sandy soils with salt contents of 1.26-1.63 g.kg^{-1} and a pH of 8-9 (Table 1). The groundwater levels of the inter-dune areas are 3-5 m deep with a salinity of 4.0-4.8 g L^{-1}, primarily composed of Cl^-, SO_4^{2-}, Na^+ and K^+ (Fan *et al*., 2008). The irrigation water quality profiles are shown in Table 2.

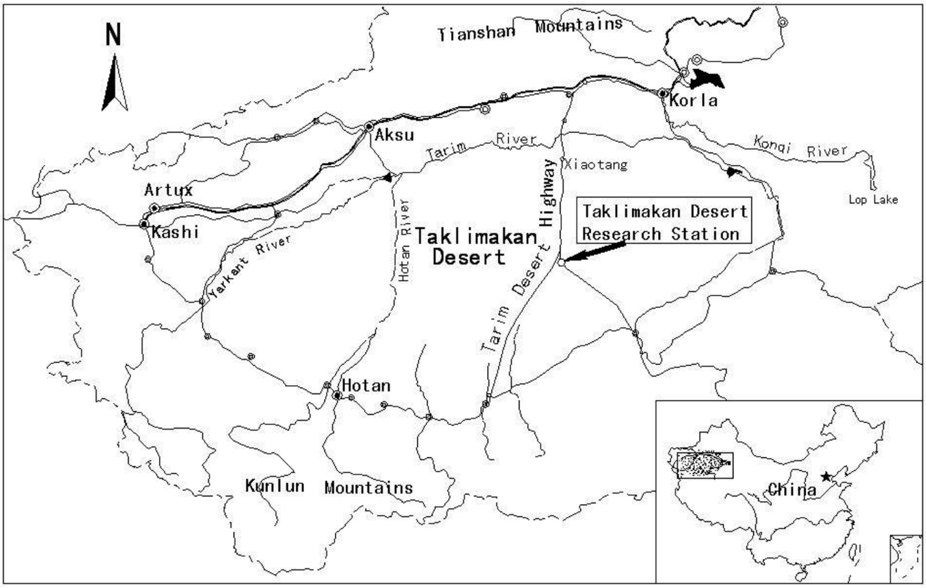

Figure 1. The Taklimakan Desert Highway located in Northwest China showing inset indicating the location of the study area

Table 1. Physical and chemical properties presented for the shifting aeolian sandy soil at the study area.

pH (1:5)	Total salt content (g kg^{-1})	Ion composition (g kg^{-1})							
		CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+
8.26	1.33	0.02	0.106	0.703	0.014	0.096	0.01	0.32	0.061

Table 2. Typical chemical properties observed in the irrigation groundwater at the study area.

pH	Conductivity (ms cm^{-1})	Salinity (gL^{-1})	Salt content (gL^{-1})	Ion composition (gL^{-1})					
				HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+ and Na^+
8.13	6.06	4.04	3.912	0.079	1.497	1.005	0.108	0.150	1.073

2.2. Soil evaporation experiments

The planting space of the study area is 1 m × 1 m, one emitter per plant, and the shelterbelt was irrigated at intervals of 15 days in March, April, May, September and October and of 10 days in June, July and August at an irrigation rate of 30 L m^{-2}. Different plants in the study area have different transpirations under such irrigation schedule (Xu *et al.*, 2008). We used Micro-Lysimeters (MLS) 20 cm in length and 10 cm in diameter to measure soil evaporation in July 2010 (Plauborg, 1995; Yan *et al*., 2012). To minimize soil disturbance, MLS were vertically pressed into the soils to a depth of 20 cm in the 5-yr shelterbelts and then dug out slightly after irrigation. In total, 12 MLS were used, and 6 MLS were used as controls, in which the salt crusts (approximately 0.5 cm thickness) were manually removed. The MLS were placed in 6 bare sandy soil sites (3 with crust, 3 without crust) and a 6 shelterbelt soils in the center of two plant rows (3 with crust, 3 without crust). Soil water contents were measured by the gravimetric method at 4 depths, 0-0.5, 0.5-5, 5-15 and 15-30 cm 30 cm from each MLS. If present, soil salt crusts were included in the 0-0.5 cm depth measurement. The MLS were weighed daily at 20:00 for 10 days (one irrigation cycle) using an electronic balance (LP-6200S, Sartorius Group, Göttingen, Sachsen, Germany). Soil evaporation for each treatment was calculated as follows:

$$ET = \frac{10\Delta m}{\pi (d/2)^2}$$

where *ET* (mm) is the soil evaporation, Δm (g) is the mass difference between two weights, and *d* (cm) is the diameter of the inner barrel. In addition, the inhibition efficiency was used to estimate the inhibition of the soil salt crusts on soil evaporation as follows:

$$I = (E_0 - E_i) / E_0 \times 100\%$$

where *I* is the inhibition efficiency, E_i is soil evaporation with salt crusts, and E_o is soil evaporation without salt crusts.

2.3. Chemical analysis

In March 2010, soil salt crusts were sampled 30 cm from the drippers in the 2-, 5-, 8-, and 11-yr shelterbelts, and shifting sandy soils were collected as controls. All samples were air-dried, sieved through a 2-mm mesh and stored for chemical analysis. SOM was determined by the potassium dichromate method. Total salt was determined by gravimetric analysis. Ca^{2+} and Mg^{2+} were determined by the EDTA volumetric method, K^+ and Na^+ were determined by flame photometry, SO_4^{2-} was determined by barium sulfate turbidity, Cl^- was determined by silver nitrate titration, CO_3^{2-} and HCO_3^- were determined by neutralization titration, and pH (soil:water = 5:1) was determined by the glass-electrode method (Bao, 2000).

3. Results and Discussion

3.1. Salt crust effects on soil moisture dynamics

Soil water contents were significantly reduced following irrigation and stabilized within a few days of the irrigation event (Figure 2). Soil water contents under the salt crusts were lower than the controls at the topsoil layers (0-5 cm) for approximately 24 hours after irrigation. Because soil crust only occurred in the topsoil, these observations suggested that the soil salt crust reduces soil evaporation with time. Salt crust formed from soluble salt crystallization and impeded the pore continuum of topsoil, so soil evaporation reduced (Zhang *et al*., 2008). Additionally, because soil moisture in the subsoil layers (5-30 cm) was higher in soils with salt crust than without, crust formation may be helpful for water storage in deep soil. Because soil evaporation was higher immediately following irrigation, it is clear that soil water content was an important factor influencing the rate of soil evaporation. The strong sunshine and low relative air humidity causes strong soil evaporation in the hinterland of the Taklimakan Desert (Yang *et al*., 1995). Meanwhile, the soil moisture deficit can restrict evaporation in dry sandy soils (Yamanaka and Yonetani, 1999), and a salt-covered surface can still reduce soil evaporation (Ullman, 1985).

3.2. Inhibition of salt crusts on evaporation

The evaporation rate decreased gradually for both bare soils in and on the margins of the shelterbelt after irrigation (Figure 3). In both soils in and on the margin of the shelterbelt, the treatment without crust exhibited an exponential or logarithmic reduction pattern of soil evaporation, while the treatment with crust exhibited a linear reduction pattern. We found that soils without crusts showed more rapid and higher total evaporation than soils with crusts, possibly due to an altered capillary rise phenomena. In the soil without crust, we observed that a dry sand layer formed in bare soils on the 3rd day following irrigation and formed in shelterbelt soils on the 5th day. A dry sand layer was considered to effectively restrict soil evaporation (Yamanaka and Yonetani, 1999). However, dry sand layers did not form in the crust treatments for the bare soils or the soils in the shelterbelt. Daily evaporation in soils with and without salt crust intersected on the 3rd day for the bare soils and on the 7th day for the shelterbelt soils. Because soils with and without salt crusts contained the same water content after irrigation, these results indicate that soil evaporation was greater for the bare soils than for the shelterbelt soils. Reductions in soil evaporation in the shelterbelt may be attributed to canopy shading effects (Raz-Yaseef *et al*., 2010).

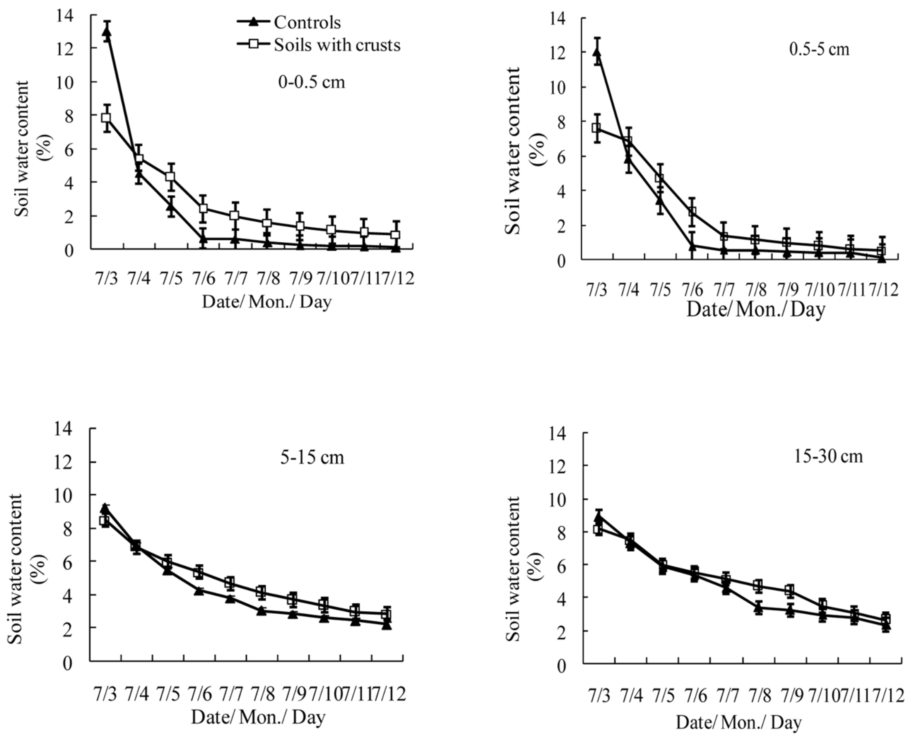

Figure 2. Soil moisture content dynamics observed in the shelterbelt at different depths. Soil crusts are included in the 0-0.5 cm depth for soils having salt crusts

Bare soils and salt-encrusted soils showed different evaporation inhibition efficiency dynamics after irrigation (Figure 4). The inhibition efficiency decreased linearly with time after irrigation and showed a clear association with soil water content. On the first day after irrigation, the inhibition efficiency was higher for bare soils (64.8%) than shelterbelt soils (58.0%). However, the inhibition efficiency decreased at a faster rate for bare soil than the soil in the shelterbelt. The faster evaporation rate of bare soils than soils in the shelterbelt (Figure3) meant that the soil water content was quickly reduced until the rate of soil evaporation of the bare soils was lower than that of the soils in the shelterbelt. The inhibition efficiency for bare soils was higher than that of the soils in the shelterbelt for the first 2 to 3 days following irrigation, but was lower from day 4 until day 10 following irrigation. The inhibitionsoil efficiency at the end was 33.0% in the shelterbelt soil which was much higher than the 13.4% observed for the bare soils, indicating effective inhibition of soil evaporation in the wetter shelterbelt soils for a long-term.

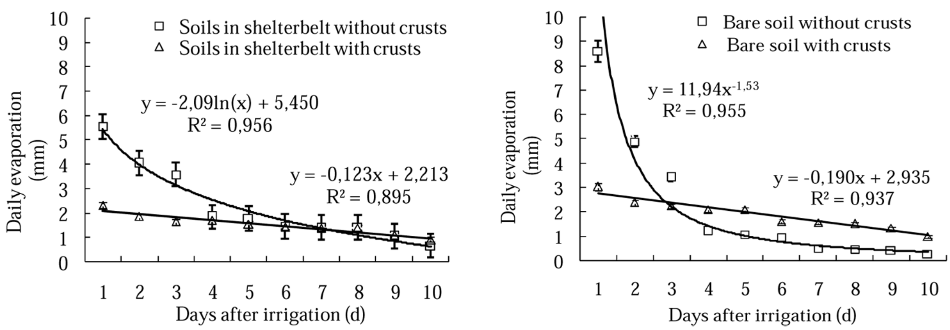

Figure 3. The effects of soil crusts on soil moisture evaporation observed after irrigation for (a) bare soils and (b) soils in the shelterbelt

3.3. Chemical dynamics affected by shelterbelts age SOM analysis

Table 3 shows the SOM contents of the soil salt crusts for treatments with different shelterbelt ages. In general, the SOM of soil salt crusts increased by 0.68, 2.19, 2.84 and 3.07g kg^{-1} in the shelterbelts irrigated for 2, 5, 8 and 11 years, respectively, compared with the controls, i.e., shifting sandy soils. Older shelterbelts shad a lower marginal rate of SOM accumulation than younger shelterbelts (Table 3). In the study area, the vegetative species of the shelterbelt are mainly deciduous shrubs, such as *Calligonum* spp., *Tamarix* spp. and *Haloxylon* spp. Because of the extremely arid environment, organic debris decomposes slowly and accumulates gradually, and the increase in SOM is closely related to shelterbelt age. SOM is an important indicator of soil fertility, soil structural function and, therefore, plant growth and development (Bockheim *et al.*, 1991; Wezela *et al.*, 2000). The age of vegetation has an impact on the chemical, physical and biological characteristics of forest soils, especially the topmost layers (Augusto *et al.*, 2002).

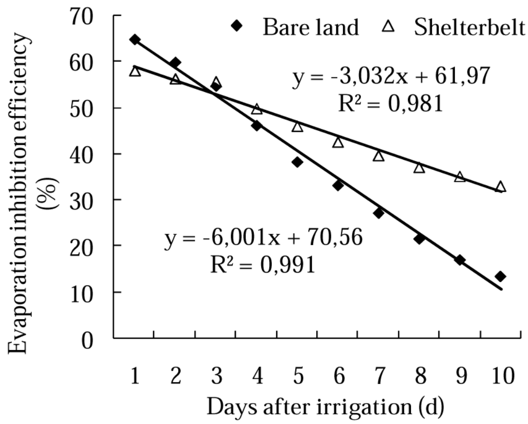

Figure 4. Inhibition efficiency dynamics of salt crusts on soil moisture evaporation exhibited after irrigation in bare land and shelterbelts

3.4. Total salt analysis

The shelterbelts irrigated for 2, 5, 8 and 11 years had 41.53, 14.56, 14.27 and 12.53 g kg^{-1}, respectively, more total salt than shifting sandy soils (Table 3). The total salt content of the soil increased within the first two years of shelterbelt irrigation. The total salt content was significantly reduced from years 2 to 5 of shelterbelt irrigation, and then slightly reduced after 5 to 11 years of shelterbelt irrigation. The total salt contents were much higher in the salt-encrusted soils than in the shifting sandy soils, but the difference diminished as the age of the shelterbelt increased. This finding is consistent with previous results from the same study area (Xu *et al*., 2006). The soluble salt content of soil is one of the important indicators for determining the degree of soil salinization. Salt injury or alkali injury to plants might occur if the soil salt content in the root zone is excessively high. The shelterbelt is drip-irrigated with water containing 4.04 g L^{-1} of salts, which is extremely saline compared to standard irrigation water. Irrigation with this quality of water results in an annual deposition of approximately 2.3 kg of salt per square meter of shelterbelt soil. This deposition causes the salt content in the topsoil to increase rapidly during initial establishment of the shelterbelt because of weak leaching effects. With continuing irrigation, salt accumulation and salt leaching occur simultaneously (Zhang *et al*., 2011), and salt accumulation in topsoil decreases over time as the soil evaporation decreasing with the continuing plant growth. Meanwhile, salt may accumulate in vegetal tissues with plant growth, but this can be ignored since it is much less than salt input from irrigation water. It appears that leaching results in a larger quantity of salts being removed from the soil solution than is accumulated. The net effect of salt leaching should be a more favorable environment for plant growth.

3.5. Ion composition analysis

Table 3 illustrates the patterns of ion content as a function of shelterbelt age, which is generally similar to the pattern observed for the total salt content. With drip-irrigation of high-salinity groundwater, the ion contents of soil salt crusts increased during the first 2 years of shelterbelt age compared with shifting sandy soils, with the exception of CO_3^{2-}. From shelterbelts 2 to 5 years of age, the ion contents were significantly reduced and then exhibited slight reductions from 5 to 11 years. Specifically, after shelterbelt planting and irrigating for several years, SO_4^{2-} in the soil salt crusts significantly increased 2.26~6.85 g kg^{-1} compared to shifting sandy soils: Cl^- significantly increased 5.32~19.40 g kg^{-1}, HCO_3^- slightly increased 0.04~0.08 g kg^{-1}, CO_3^{2-} remained relatively constant, Mg^{2+} increased 0.43~1.64 g kg^{-1}, Na^+ increased 3.08~11.72 g kg^{-1}, Ca^{2+}, increased 0.24~0.56 g kg^{-1} and K^+ increased -0.01~0.71 g kg^{-1}. In general and particularly in the two years following establishment of the shelterbelt, there were relatively large increases in Cl^-, Na^+ and SO_4^{2-}, moderate increases in Mg^{2+}, K^+, and Ca^{2+}, a slight increase in HCO_3^-,and little change in CO_3^{2-}. High ion concentrations may result in ion toxicity or osmotic stress to the plants, which could affect plant growth and possibly lead to plant death.

Table 3. Soil organic matter (SOM), total salt ion composition and pH of shifting sandy soil and soil salt crusts of different shelterbelt ages

Treatments	pH	SOM (gkg^{-1})	Total salt (gkg^{-1})	Ion composition (gkg^{-1})							
				Cl-	SO_4^{2-}	CO_3^{2-}	HCO_3^-	Na^+	Mg^{2+}	Ca^{2+}	K^+
Shifting sand	8.26a	0.74d	0.13d	0.38d	0c	0a	0.10a	0.16c	0.01d	0.07d	0.03c
2 yr	8.86a	1.42c	41.66a	19.78a	6.85a	0a	0.18a	11.88a	1.65a	0.64a	0.74a
5 yr	8.62a	2.93b	14.69b	6.56b	3.32b	0a	0.15a	3.88b	0.76b	0.46b	0.41b
8 yr	8.3a	3.58ab	14.40b	5.91bc	2.94b	0a	0.14a	3.69b	0.63bc	0.36bc	0.40b
11 yr	7.93a	3.81a	12.66c	5.70bc	2.26b	0a	0.14a	3.24b	0.44c	0.31c	0.02c

(Means followed by different letters are significantly different at $p< 0.05$ using Fisher's LSD).

Previous research has indicated that different ions cause different injuries to different plants (Kingsbury and Epstein, 1986; Fortmeier and Schubert, 1995; Keutgen and Pawelzik, 2009). We found that the relative quantities of ions composing the soil salt crusts mirrored the ion composition of the irrigation water (Table 2), which illustrates that the ion contents of the soil in the study area were greatly affected by the irrigation water. In shifting sandy soil, the anions were primarily Cl^- and HCO^{3-}, with a moderate amount of SO_4^{2-} and a very small amount of CO_3^{2-}. Cations were primarily Na^+ and Ca^{2+} with moderate amounts of Mg^{2+} and K^+ (Table 1). Whether these ions cause toxicity or osmotic stress to plants in the Taklimakan Desert Highway Shelterbelt requires further study.

3.6. pH analysis

The pH of the soil salt crusts in the shelterbelts, regardless of age, was alkaline, but gradually neutralized with shelterbelt age. The pH of the soil salt crusts in the shelterbelt that had been established for 11 years was lower than that of the shifting sandy soil (Table 3). This trend of changing pH was consistent with the change in the total salt contents and the ion composition of the soil salt crusts. The increase of soluble salts, especially Na^+ and Cl^- may result in soil salinization or alkalization. It is known that pH has substantial effects on soil fertility, and plants have certain requirements for soil pH. It has been reported that excessive sodium salt, calcium salt and magnesium salt in the soil solution will restrict plant growth and can lead to plant death if the soil salt content within the root zone is excessively high (Zhang *et al*., 2004). However, under such pH conditions, all shelterbelt trees in our studied area grew well and showed no obvious salt injury; even the shelterbelt trees planted for two years grew well at the pH of 8.86. Previous long-term studies have indicated that plants in the shelterbelt grow well under similar pH and soil conditions (Li *et al*., 2005; Di *et al*., 2005).

Conclusions

Water resource conservation is one of the key issues for sustainable agricultural and ecological development in arid regions. These results demonstrated that soil salt crusts can effectively inhibit soil evaporation in the Taklimakan Desert Highway Shelterbelt when drip-irrigated with high-salinity groundwater. In the shelterbelt, soil evaporation inhibition efficiency was much higher for the salt-encrusted soils than for bare soils. Our study also demonstrates that the chemical properties of salt crusts are generally not harmful to plant growth for a long time periods. While this finding speaks to the sustainability of saline groundwater utilization and shelter-forest construction and management in arid lands, further studies are needed to assess the ecological and environmental effects of soil salt crusts, especially on plant growth.

Acknowledgements

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