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The salt accumulation at the shifting aeolian sandy soil surface with high salinity groundwater drip irrigation in the hinterland of the Taklimakan Desert

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The EC analysis and water serial sampling was performed in the Tarim Desert Highway shelterbelt to explore the water and salt dynamics of the shallow aeolian sandy soil (0—30cm) under high salinity groundwater drip irrigation. It was found that in one irrigation cycle, the EC of the shallow shifting aeolian sandy soil (0—30cm) increased while the water content decreased. The EC of the surface aeolian sandy soil at the wetting front was far greater than that of the wetting area or the outside of the wetting area. During the irrigation cycle, the EC of the wetting front and the wetting area changed at a significant magnitude, whereas the EC of the outside of the wetting area remained largely steady. The horizontal influence distance of drip irrigation on the salt accumulation at the soil surface was about 100 cm, and the vertical influence depth was 5 cm. The three most abundant ions in the accumulated salt at the aeolian sandy soil surface were Na^+, Cl^- and SO_4^{2-}. The salt accumulation at the soil surface was influenced by air temperature, wind speed, mineralization of irrigation water, sand burial thickness, soil texture, and litter content.

hinterland of the Taklimakan Desert, drip irrigation with saline water, salt accumulation at soil surface, shifting aeolian sandy soil, influence factors

The salt accumulation at soil surface is determined by the salt status at the soil surface and the spatiotemporal change in soil salt distribution. The soil water and soil salt dynamics have been extensively researched in relation to irrigation method, irrigation water quality, soil types, and many other factors[1−10]. Nevertheless, the results were mainly on salt accumulation at plough horizon after irrigation, and the research on the dynamic salt accumulation at soil surface is relatively scarce. In particular, there is no report on the dynamic salt accumulation at the shifting aeolian sandy soil surface with high salinity groundwater drip irrigation in the hinterland of the Taklimakan Desert.

Most of the Tarim Desert Highway lies in the shifting sandy land that has serious blown sand disasters, therefore the shelterbelt was built to ensure the safety on the highway[11]. The Tarim Desert Highway shelterbelt is 436 km in length, 72—78 m in width, with a total area of 3128 hm^2. The species are mainly highly stress-resistant shrubs with excellent windbreak and sand fixation properties, such as *Calligonum* L., *Tamarix* L., *Haloxylon* Bunge, etc.

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The implementation of the shelterbelt affects the physical and chemical properties of the soil, and results in further complications in soil evolution[12－14]. Salt-injury is a major threat to the shelterbelt because of salt accumulation at the soil surface by long-term drip irrigation with high salinity groundwater[6,8]. In this work, the soil evolution in the shelterbelt was examined in order to seek a theoretical guideline for the utilization of saline groundwater and the maintenance of the Tarim Desert Highway shelterbelt.

1 Experimental area

The experiments were conducted in the Taklimakan Desert Research Station/Tazhong Botanical Garden, Chinese Academy of Sciences, in the hinterland of the Taklimakan Desert in the Xinjiang Uygur Autonomous Region (approximately 39º01′N, 83º36′E, 1100 m a.s.l.).

The climatic characteristics are: mean annual air temperature 12℃, average July temperature 28.2℃, maximum sand surface temperature 75.3 ℃ , average December temperature –8.1℃, maximum air temperature 45.6℃, minimum air temperature –22.2℃, active accumulated temperature (⩾10℃) 4 618.6℃. The climate is also extremely arid, with an annual average precipitation of 24.6 mm, an annual average relative humidity of 29.4%, a total annual low humidity days (⩽30%) of 246.6 d, and an annual mean evaporation of 638.6 mm. The serious blown sand disasters are characterized by an annual average wind a speed of 2.5 $m \cdot s^{-1}$, a maximum instantaneous wind speed of 20.0 $m \cdot s^{-1}$, and a total annual sand-shifting windy days of more than 130 d. Natural vegetations are rare in the Taklimakan Desert hinterland except for a limited coverage of *Tamarix ramosissima* and *Calligonum leucocladum* in the lowlands between the dune chains. The ground landscape is mainly high mobile dunes and large complex dune chains. The soil is mainly shifting aeolian sandy soil that has little nutrient, low microelement level, poor moisture capacity and limited fertilizer retention. The salt content is 1.26－1.63 $g \cdot kg^{-1}$, and the pH is 8－9. The salt profile of the aeolian sandy soil in the experimental area is shown in Table 1.

The depth of the groundwater in the lowlands between the dune chains is 3－5 m, and the mineralization is 4.0－4.8 $g \cdot kg^{-1}$, mainly Cl^-, SO_4^{2-}, Na^+ and K^+. The water quality profile is shown in Table 2.

2 Materials and methods

The soil salt accumulation experiment with high salinity groundwater drip irrigation was performed in one irrigation cycle, from Jun. 9 to 18, 2006. The sampling sites were chosen in the artificial shelterbelt with saline groundwater drip irrigation in the hinterland of the Taklimakan Desert. The mineralization of groundwater was 4.04 $g \cdot L^{-1}$. All samples were collected at 9:00 am. The sampling points were the wetting areas, the wetting fronts, and outside the wetting areas around the drippers. Soil samples were collected at the surface and also at depths of 0－5 cm, 5－15 cm, and 15－30 cm, respectively. All samples were divided into two equal portions and submitted to water content analysis and conductivity measurement. All values were averaged from four measurements. a The different soil textures are shown in Table 3 and the experimental design of the salt accumulation at soil surface under various external factors is shown in Table 4.

The soil water content was measured by the sample mass loss after dehydration at 105℃ for 24 h. The soil salt content was determined by gravimetric analysis (HB/T 51－1999); Ca^{2+} and Mg^{2+} were tested by EDTA titrations (GB/T 7476－1987 and GB/T 7477－1987); SO_4^{2-} was determined by barium sulfate turbidity (GB 7871－1987); Cl^- was determined by silver nitrate titration (GB/T 11865－1985); CO_3^{2-} and HCO_3^- were de-

Table 1 Salt profile of the aeolian sandy soil in the experimental area

pH	Dried litter ($g \cdot kg^{-1}$)	Soluble salt content ($g \cdot kg^{-1}$)						
		CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^++Na^+
8.26	1.47	0.02	0.10	0.55	0.27	0.05	0.03	0.41

Table 2 Irrigation groundwater quality profile in the experimental area

pH	Conductivity ($ms \cdot cm^{-1}$)	Mineralization ($g \cdot L^{-1}$)	Salt content ($g \cdot L^{-1}$)	Ion composition ($g \cdot L^{-1}$)					
				HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	$K^+ + Na^+$
8.13	6.06	4.04	3.912	0.079	1.497	1.005	0.108	0.150	1.073

Table 3 Soil particle compositions of different soil textures

Soil texture	Clay particle (%)	Silt particle (%)	Sand particle (%)
Sandy soil	0.27	12.35	87.48
Sandy loam soil	26.37	26.89	46.74
Clay	52.47	41.42	6.11

Table 4 The experimental design of salt accumulation on soil surface under different factors

Influencing factors	Experimental time	Experimental design	Sampling method	Experimental notes
Air temperature	In early August 2007	20℃, 35℃, 60℃	Collect surface soil samples every 12h after sufficient irrigation, determine conductivities after air-dry.	Control the temperatures by air-condition and oven, mineralization of irrigation water is 4.04 $g \cdot L^{-1}$, place 9 evaporators every temperature.
Wind speed	In early August 2007	0 $m \cdot s^{-1}$, 1.0 $m \cdot s^{-1}$, 1.6 $m \cdot s^{-1}$	Collect surface soil samples every 12h after sufficient irrigation, determine conductivities after air-dry.	Fan as power, test wind speeds with handhold anemometer, mineralization of irrigation water is 4.04 $g \cdot L^{-1}$, place 9 evaporators every temperature.
Mineralization of irrigation water	In early July 2007	0 $g \cdot L^{-1}$, 5 $g \cdot L^{-1}$, 10 $g \cdot L^{-1}$, 15 $g \cdot L^{-1}$, 20 $g \cdot L^{-1}$, 25 $g \cdot L^{-1}$, 30 $g \cdot L^{-1}$	Collect soil crusts samples 10 day later after sufficient irrigation, determine conductivities after air-dry.	Under natural conditions, 3 replications, take the average value.
Sand burial thickness	In late April 2007	Check, 5 cm, 10 cm, 15 cm, 20 cm, 25 cm, 30 cm, 35 cm, 40 cm	Collect soil crusts samples of wetting front after sand burial and irrigation for 3 months, determine conductivities after air-dry.	Bury the burette into shifting sand land under natural conditions, 3 replications, take the average value.
Soil texture	In late July 2007	Sandy soil, sandy loam soil, clay soil	Collect surface soil samples at 21:00 everyday and determine conductivities after air-dry.	Mineralization of irrigation water is 4.04 $g \cdot L^{-1}$, place 12 evaporators every soil texture.
Litter content	In late November 2006	Collect soil samples in shifting sand land, shelterbelts of 2 years, 5 years, 8 years, 11 years	Collect soil crusts samples after stopping irrigation, determined total salt contents, 8 ions, and conductivities.	Sampling points are in the shelterbelts drip-irrigated with saline water of 4.04 $g \cdot L^{-1}$, 3 replications, take the average value.

termined by neutralization titration; and the conductivity was determined (soil : water = 5 : 1) with the conductivity-thermometer SY-3[15].

3 Results and analysis

3.1 Salt accumulation at the shifting aeolian sandy soil surface

Most of the soil salt comes from irrigation water, and the water movement determines the salt accumulation at soil surface. The extremely dry Taklimakan Desert has little precipitation but strong evaporation. Natural precipitations have negligible leaching effect on soil salts, and soil moisture quickly moves upward. The sampling analysis showed that in one irrigation cycle, the soil water content of the wetting area and the wetting front decreased gradually (Figure 1). The soil water content of the wetting area decreased most drastically until the fifth day and remained steady afterwards. The soil water content of the wetting front also decreased rapidly until the seventh day and remained steady afterwards. The soil water content of the outside of the wetting area basically maintained a low and relatively stable level at 0.24%. Because the irrigation water reached the wetting area more readily than the wetting front and the outside of the wetting area, the soil water content of the wetting area was the highest.

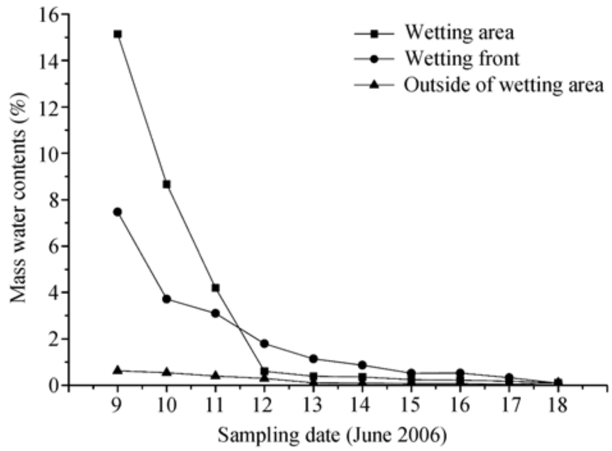

Figure 1 Water dynamics of the shallow aeolian sandy soil.

Conductivity is one important indicator of soil salinity. It can be seen from Figure 2 that the conductivity of the wetting front was the highest, and the outside of the wetting area had higher conductivity than the wetting area. The conductivity of the wetting area and the wetting front increased over time within the irrigation cycle, whereas the conductivity of the outside of the wetting area remained largely stable. This trend is the result of the salt accumulation at soil surface by evaporation and the salinity leaching effect of drip irrigation. Drip irrigation forms numerous durative small water entities to leach salinity to the lower layer soil, and simultaneously push the salt outward in a pulse manner, thus resulting in salt accumulation at the wetting fronts.

It was found that the soil salt crusts between emitters were independent in 4 m×4 m shelterbelt. The salt crusts formed circles around the emitters at a radius of about 1 m. The wetting front of the highest conductivity was about 40 cm from the emitter. Because most of the space between the plants in the Tarim Desert Highway shelterbelt is 1m×1m, the soil crusts between emitters have connected into each other. In other words, the range of drip irrigation influence on salt accumulation at the aeolian sandy soil surface is about 1 m.

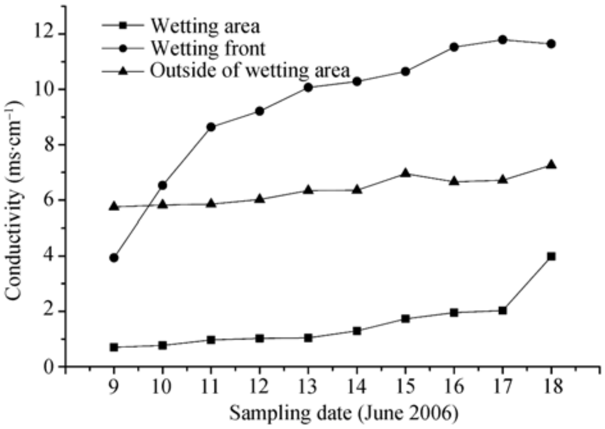

Figure 2 EC dynamics of the shallow aeolian sandy soil.

According to the aeolian sandy soil water dynamics (Figure 3), the soil water content in the crust layer decreased most sharply until the fourth day to steady level. The water content of the 0—5 cm soil decreased less sharply and reached steady level on the fifth day. The 5—15 cm and 15—30 cm soil had gradual dehydration, and the turning points of the dehydration rate were the fourth day and the second day. On the first day of irrigation every layer was basically saturated, and the soil water contents of every layer were nearly the same. The soil crust was on the surface and had the most active evaporation, thus the smallest water content. Salt is brought into soil by irrigation water and accumulates continuously. At the same time, salt moves from the inner soil layer to the outer soil layer as a result of water evaporation, therefore the salt content in the shallow soil increases constantly (Figure 4). The increase of salinity in the crust layer and the 0—5 cm soil was the most obvious, whereas the salinity of 5—15 cm and 15—30 cm soil had a barely noticeable increase. The soil salt content of these four layers reached maximum at the end of the irrigation cycle, at which time the crust layer and the 0—5 cm soil had significantly greater salinity than the 5—15 cm and 15—30 cm soil. The results indicate that salt accumulation at soil surface under drip irrigation mainly influenced the 0—5 cm soil, and the lower layers were hardly affected.

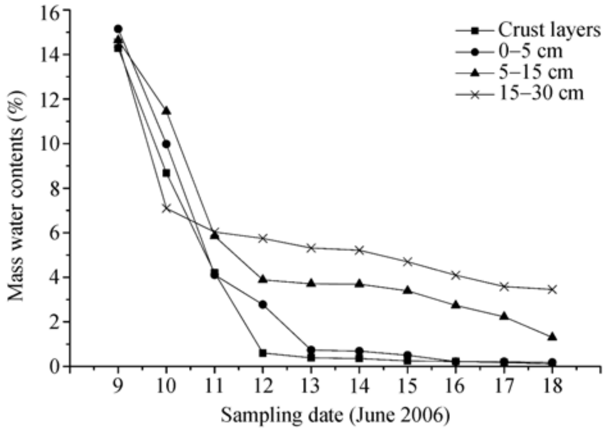

Figure 3 Water dynamics of wetting area in vertical direction.

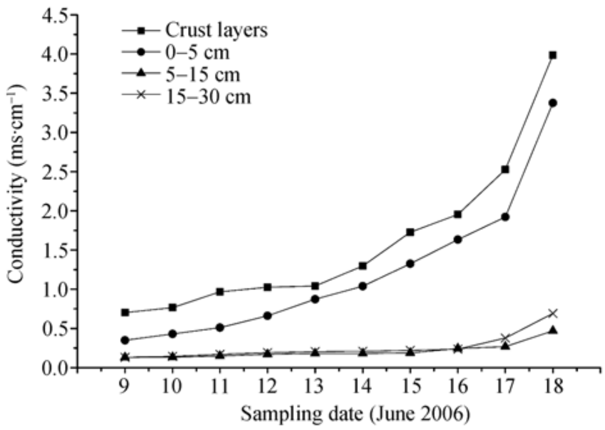

Figure 4 EC dynamics of wetting area in vertical direction.

The predominant anions in the shifting aeolian sandy soil are Cl^- and SO_4^{2-}, and the cations are mainly Na^+ and Ca^{2+}, with a very small amount of Mg^{2+} and K^+ (Table 1). Crusts form easily on the soil surface after drip irrigation with saline water[6,10]. By analyzing the chemical properties (Figure 5) of the aeolian sandy soil crust formed in different irrigation years, it was found that Cl^- and SO_4^{2-} were the most abundant anions, and Na^+ was the most abundant cation. This analysis shows that the salt accumulated on the aeolian sandy soil surface consisted of mainly Na^+, Cl^- and SO_4^{2-}, which is consistent with the ion composition of the irrigation water.

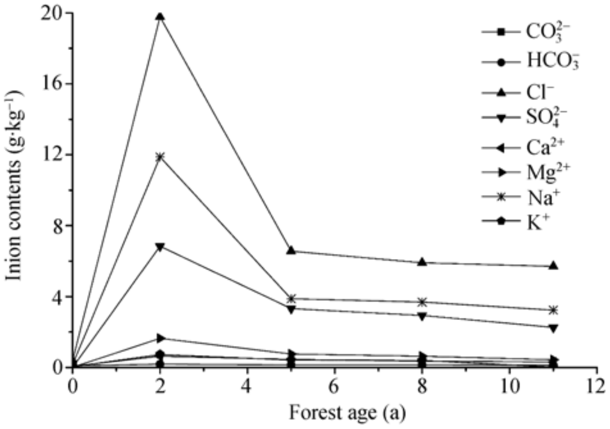

Figure 5 Annual variation of ions contents of salt crusts in shelterbelts of different ages.

In short, the soil water content of the crust layer and the shallow soils reduced in one irrigation cycle, and the EC increased gradually. The EC of the soil salt crust in the wetting front was much higher than that of the wetting area and the outside of the wetting area. The EC of the wetting front and the wetting area changed in significant magnitude in the irrigation cycle, whereas the EC of the outside of the wetting area was largely steady. The drip irrigation had an influence range of about 1 m on salt accumulation at the aeolian sandy soil surface, and a vertical influence depth of 5 cm. The salt accumulated on the soil surface consisted mainly of Na^+, Cl^- and SO_4^{2-}.

3.2 Effect of different factors on salt accumulation at the soil surface

(i) Air temperature. According to Figure 6, at any given time in the irrigation cycle, the EC of the soil surface at an air temperature of 60℃ was higher than that of 30℃, both of which higher than that of 20℃. The rate of EC increase at 60℃ was also higher than that of 30℃, and the EC at 20℃ remained largely steady during the irrigation cycle. Because soil water evaporation is more active at higher temperature, more salt is brought upward to the soil surface by soil water, consequently resulting in salt accumulation at the soil surface. Therefore, the air temperature has a significant effect on the salt accumulation at the shifting aeolian sandy soil surface.

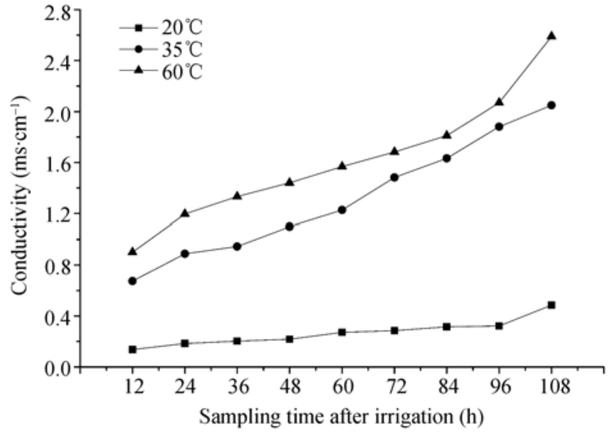

Figure 6 Salt accumulation process at the surface of aeolian sandy soil under different air temperatures.

(ii) Wind speed. According to Figure 7, at any given time in the irrigation cycle, the EC of the soil surface at a wind speed of 1.6 $m \cdot s^{-1}$ was higher than that of 1.0 $m \cdot s^{-1}$, both of which were higher than that of 0 $m \cdot s^{-1}$. The rate of EC increase at a wind speed of 1.6 $m \cdot s^{-1}$ was also higher than that of 1.0 $m \cdot s^{-1}$, and the EC changed very little during the irrigation cycle when there was no wind. High wind speed promotes soil water evaporation and consequently facilitates salt accumulation at the soil surface. Therefore, the wind speed has a significant effect on the salt accumulation at the shifting aeolian sandy soil surface.

(iii) Mineralization of irrigation water. According to Figure 8, the EC of soil surface increased at a diminishing rate with rising mineralization of irrigation water

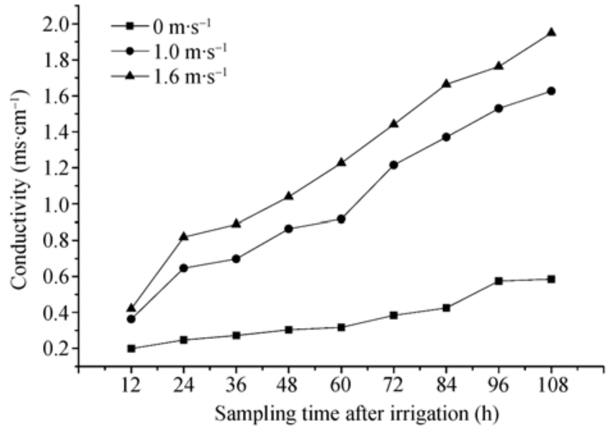

Figure 7 Salt accumulation process at the surface of aeolian sandy soil under different wind speeds.

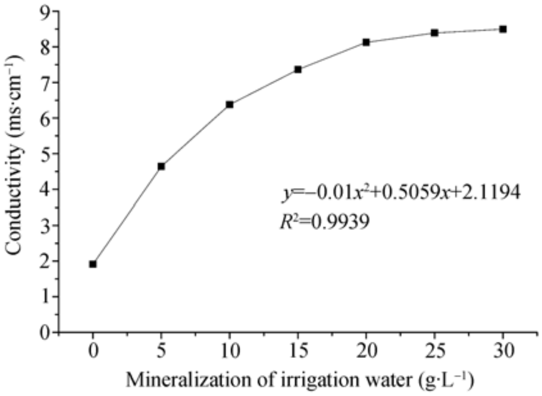

Figure 8 Relationship between mineralization of irrigation water and EC of surface aeolian sandy soil.

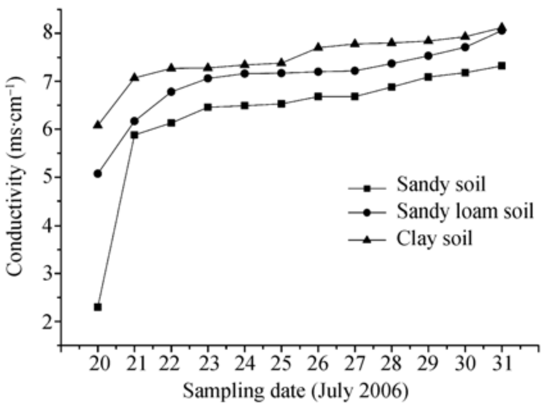

Figure 10 Salt accumulation process at soil surface under different soil textures.

($\leqslant$30 g·L^{-1}). Under sufficient irrigation condition, the irrigation water of higher mineralization brings more salt into the soil, thus resulting in more salt accumulation at the soil surface. The regression equation of EC is expressed as

$$y = -0.01x^2 + 0.5059x + 2.1194,\ (0 \leqslant x \leqslant 30)$$

$$R^2 = 0.9939.$$

The equation was excellently fit for the experimental data. Therefore, the mineralization of irrigation water has a significant effect on the salt accumulation at the shifting aeolian sandy soil surface.

(vi) Sand burial thickness. According to Figure 9, the EC of the soil salt crust reached maximum when the sand burial thickness was 10 cm, and the salt crust ceased to develop when the sand burial thickness exceeded 35 cm. Because the capillarity is weak in shifting sandy land, if the sand burial is thick enough, the capillarity water will be unable to reach soil surface and the salt crust will not develop[16,17].

(v) Soil texture. According to Figure 10, the EC of the three soil textures increased gradually after sufficient irrigation. The EC of the sandy soil was the lowest and changed in the greatest magnitude. The EC of the clay soil was the highest and changed in the least magnitude. The water holding capacity of the three textures are: clay >sandy loam>sandy soil. After sufficient irrigation, the soil water content of all textures reached field capacity, therefore for each unit volume clay soil held more water than sandy loam soil, and sandy loam soil held more water than sandy soil. Because higher water content led to higher salt content, the clay soil had the highest salt content, and the sandy soil had the least.

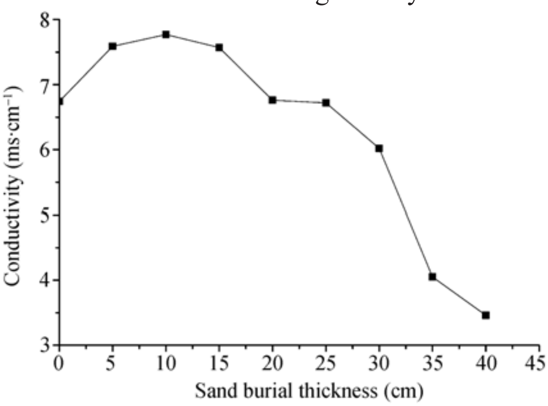

Figure 9 Relationship between sand burial thickness and EC of surface aeolian sandy soil.

(vi) Litter content. The soil structure and soil composition changes with shelterbelt planting over irrigation years[13−15]. Because all of the three main species (*Calligonum* L., *Tamarix* L., and *Haloxylon* Bunge) of the shelterbelt are deciduous shrubs or semi-shrubs, litter accumulates continuously at the soil surface. Litter has a strong inhibition effect on soil water evaporation, and consequently inhibits salt accumulation at the soil surface[18].

Both natural precipitations and long-term drip irrigation have leaching effect on surface soil salt[19,20]. According to Figure 11, the salt content of the crusts decreased gradually over the irrigation years, which resulted from a combination of litter-induced inhibition and salt leaching. The inhibition by litter is more pronounced because litter weakens salt leaching by water interception. The increase in litter content, the salt leaching, and the improvement of the aeolian sandy soil in the shelterbelt all reduce the salt content in the crusts. Therefore, the salt content of the crusts increases in the short term as a result of drip irrigation with high salinity groundwater, but decreases gradually over the irrigation years.

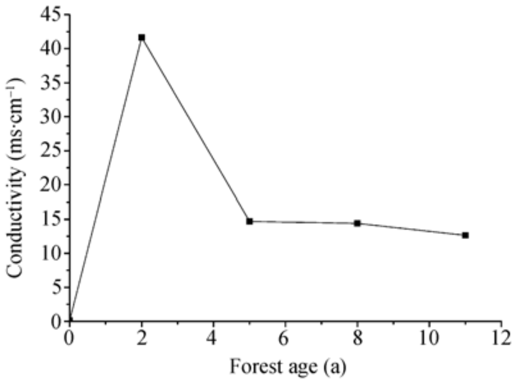

Figure 11 Relationship between EC of soil salt crusts and forest ages.

4 Conclusions and discussions

The extremely arid hinterland of the Talimakan Desert has very active soil water evaporation and soil surface salt accumulation. The salt accumulation at aeolian sandy soil surface and the soil moisture dynamics under high salinity groundwater drip irrigation were found to have the characteristics of: (1) In one irrigation cycle, the soil water content of the soil salt crust decreases gradually and the soil salt content increases gradually. The salt content of the wetting front is much higher than that of the wetting area and the outside of the wetting area. During the irrigation cycle, the salt content of the wetting area and the wetting front changes significantly, but the salt content of the outside of the wetting area remains largely steady. The influence range of drip irrigation on the salt accumulation at soil surface is about 1 m. In the vertical direction, the water content of every soil layer reduces and the soil salt content increases gradually. The vertical influence depth of drip irrigation is 0—5 cm. The salt accumulated at the aeolian sandy soil consists of mainly Na^+, Cl^- and SO_4^{2-}, which is in good agreement with the ion composition of the irrigation water. (2) The salt accumulation at the soil surface is influenced by air temperature, wind speed, mineralization of irrigation water, sand burial thickness, soil texture, and litter content. High temperature, high wind speed, and high mineralization of irrigation water will promote salt accumulation. Sand burial is beneficial to salt accumulation when the burial thickness is ≤10 cm. When the burial thickness is more than 10 cm, the salt accumulation is inhibited.

During high salinity groundwater drip irrigation, salt accumulation and leaching take place simultaneously. Salt accumulation is dominant over leaching in the early stage of irrigation, and the salt content increases gradually. As the shelterbelt matures, the litter accumulation and the improvement in soil structure persistently inhibit the salt accumulation, thus leaching eventually becomes dominant over salt accumulation, and salt content of the crusts eventually decreases.

The Taklimakan Desert usually has very little precipitation. The salt crust at the soil surface normally does not influence the growth of the shelterbelt vegetation, but unexpected strong precipitation can leach salt into deep layer soil, and may result in salt injury to plants if the salt arrives at the main distribution layer of the plant roots[21]. The roots of *Calligonum* L. are horizontal and have relatively shallow distribution[22]. Therefore, the salt tolerance of *Calligonum* L. is relatively poor. In particular, *Calligonum* L. of 1—2 years old can be easily harmed. The precipitation intensity in the Taklimakan Desert is normally less than 30 mm. The root distribution of *Calligonum* L. develops as the plant matures, and the salt content of the crust decreases over the irrigation years, thus *Calligonum* L. of several years old is resistant against salt injury. The *Calligonum* L. of 1—2 years old defends salt injury poorly and needs extra attention.

The salt accumulation at soil surface should be minimized to reduce the amount of salt available for leaching by unexpected strong precipitation and thus prevent salt injury. It was shown that sand burial at a thickness of ≥35 cm could effectively inhibit salt accumulation at the soil surface, therefore burying capillary tube ≥35 cm with sandy soil can be considered when the shelterbelt is constructed. Also, the application of organic fertilizer, soil amendment and evaporation inhibitor can reduce the salt accumulation at the soil surface by improving the soil structure. The irrigation with saline groundwater should be performed with reduced frequency and increased volume in order to promote self-leaching. The salt tolerance of each plant species in different growth stage should also be fully considered to avoid salt injury, and the soil salt should be monitored on a regular basis.

The rational use of saline groundwater for irrigation is an important solution to water resource crisis, and has broad prospects for research and application. During saline water irrigation, the salt accumulation and distribution at the soil surface is affected by many factors, such as soil property, irrigation water quality, air temperature, wind speed, land management practice and etc. Further research is needed in this area.

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