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Survival and growth of three afforestation species under high saline drip irrigation in the Taklimakan Desert, China

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Abstract. Afforestation of shelterbelts is a sustainable practice to protect highways from shifting sand dunes in desert areas. The Taklimakan Desert Highway Shelterbelt (TDHS) in China is known as "the Great Green Wall of Taklimakan Desert" and borders a 436-km distance along the highway. This study assessed the early survival, above-ground growth, and root growth of three salt- and drought-tolerant plant species (*Calligonum aborescens* Litv., *Tamarix ramosissima* Ledeb., and *Haloxylon ammodendron* (C. A. Mey.) Bunge) in TDHS; those were drip-irrigated with local high saline groundwater. The results demonstrated that more than 80% of *Haloxylon ammodendron* seedlings could survive regardless of irrigation water salinities ranging from 2.82 to 29.70 g/L. In contrast, survival rates of *Calligonum aborescens* seedlings were greater than 65% when using irrigation water salinities ≤13.99 g/L and less than 50% when irrigated with water having salinities of 20.99–29.70 g/L, respectively. However, plant survival rates of *Tamarix ramosissima* were much lower than 50% when irrigated with water having salinities >4.82 g/L. Furthermore, under the same salinity, the height, crown width, and maximum width of basal stems were the greatest for *Calligonum aborescens* plants and the lowest for *Tamarix ramosissima* plants. Root length varied among the species depending on tree age and the applied water characteristics. We conclude that afforestation is feasible with saline water in this extreme arid shifting desert, particularly *Calligonum aborescens* plants should be grown at the outer margin of the shelterbelt due to its faster growth to more quickly stabilize the shifting sand. Our study may provide a good resolution for afforestation and marginal saline water utility in most arid and semiarid regions.

Key words: artificial shelterbelt; drip irrigation; growth process; saline groundwater; seedling survival; Taklimakan Desert.

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Introduction

Desertification is a global concern and must be controlled for ecosystem preservation in many arid and semiarid regions. Vegetation restoration has been regarded as an effective ecological measure for desertification control and has been widely implemented in many desert regions around the world (Li 2004, Lei et al. 2008*b*, Wei et al. 2012). Afforestation in desert areas with shifting sand dunes presents a formable challenge due to lack of high-quality water, soil salinization, and sand blasting and burial of vegetation. These challenges are at the forefront of developing sustainable afforestation practices in the Taklimakan Desert, China (Zhang et al. 2008*a*, Huang and Pang 2012).

The primary problem encountered when trying to establish and support vegetation in arid ecosystems is the availability of good quality water for plant growth. Because of the water shortage, saline water is widely used for irrigating vegetation to overcome the water scarcity (Xu et al. 2006, Verma et al. 2012). However, the solutes in groundwater may increase soil salt contents (Zhang et al. 2008*a*) and affect plant growth and survival in irrigated areas (Schachtsiek et al. 2014, Sperling et al. 2014). When exposed to salt stress, plant growth may be influenced by the osmotic effects on water uptake and disrupted ion homeostasis in the plant cells that may cause an inhibited metabolism and damaged membranes. Plants under salt stress typically require more energy to adapt to the harsh environment and decrease the risk of salt-injury (Greenway and Munns 1980, Joset et al. 1996, Tester 2003, Tripler et al. 2007, 2011).

The Taklimakan Desert, which is the second largest shifting sand desert in the world, is located in north-western China. The Taklimakan Desert is called "The Sea of Death" because of the large expanse of shifting sand dunes and extreme drought conditions. This region receives very limited precipitation that averages 25 mm/yr and has a high evaporative potential that averages 3639 mm/yr (Lei et al. 2008*a*, *b*). The Taklimakan Desert Highway was constructed in 1997 and is oriented in the north to south direction across the desert. A mechanical sand prevention system was previously constructed to stabilize shifting sand dunes which would otherwise result in the burial of the highway. The straw checkerboard prevention system, however, was buried by the shifting sand about 3–4 yr after installation (Lei et al. 2008*b*). As a result, the Taklimakan Desert Highway Shelterbelt (TDHS), also called "the Great Green Wall of Taklimakan Desert" was constructed to protect the highway from shifting sand burial. The shelterbelt consists of *Calligonum aborescens* Litv., *Tamarix ramosissima* Ledeb., *Haloxylon ammodendron* (C. A. Mey.) Bunge, *Nitraria tangutorum* Bobr., *Populus euphratica* Oliv., and *Elaeagnus angustifolia* Linn., etc. grown along the highway. These plant species are highly salt-tolerant and drought-resistant with excellent windbreak and sand fixation properties (Zhang et al. 2009). These species were identified for the shelterbelt through plant introduction and adaptation evaluation studies that have been conducted for more than 10 yr (Zhang et al. 2009). As groundwater in the region is high in salinities (2.58–29.70 g/L), plants grown in the TDHS are typically drip-irrigated with local saline groundwater (Xu et al. 2006). Risks associated in using highly saline water as a plant water source include poor seed germination, reduced seedling growth, and reduced plant vigor (Sairam and Tyagi 2004, Paz et al. 2012, Riccardi et al. 2014, Sperling et al. 2014, Zhao et al. 2014).

Seedling growth and survival under harsh environmental conditions are very important plant properties when evaluating species' feasibility for use in afforestation. Although *Calligonum aborescens*, *Tamarix ramosissima*, and *Haloxylon ammodendron* have performed well during practical plant introduction experiments, their growth and survival in the natural environment has not been scientifically documented. Thus, this study was designed to assess the early growth and survival of these three species under drip irrigation using highly saline groundwater when evaluating the feasibility and sustainability of multiple plant species that may be used for afforestation along the TDHS.

Materials and Methods

Study area

The study was conducted at multiple monitoring sites along the TDHS (Fig. 1) which was constructed in the spring of 2003. The annual mean air temperature of the study area is 12.4°C, with the coldest monthly mean temperature of −8.1°C in December and the warmest monthly mean temperature of 28.2°C in July. Average annual precipitation is 24.6 mm, but annual potential evaporation is 3639 mm. Thus, this region is considered to be under hyper arid conditions. Average annual wind speed is 2.5 m/s, but maximum speeds in excess of 20.0 m/s may occur on more than 130 d/yr and results in shifting sands and the movement of sand dunes.

The desert landscape is composed of primarily mobile dunes and large complex dune chains. Natural vegetation in the study areas is nearly nonexistent, except for a few extreme drought-resistant shrubs (*Tamarix taklamakanensis* M.T. Liu and *Calligonum taklimakanensis* B.R. Pan & G.M. Shen, etc.) that grow in some areas where there is shallow groundwater in the inter-dune areas. The soils are shifting eolian sandy soils with limited nutrients, salt contents of 1.26–1.63 g/kg, and pH values of 8–9 (Table 1). Groundwater levels within the inter-dune areas are typically 3–5 m with salinity levels of 2.82–29.87 g/L. The water contains primarily Cl^-, SO_4^{2-}, Na^+, and K^+ (Zhang

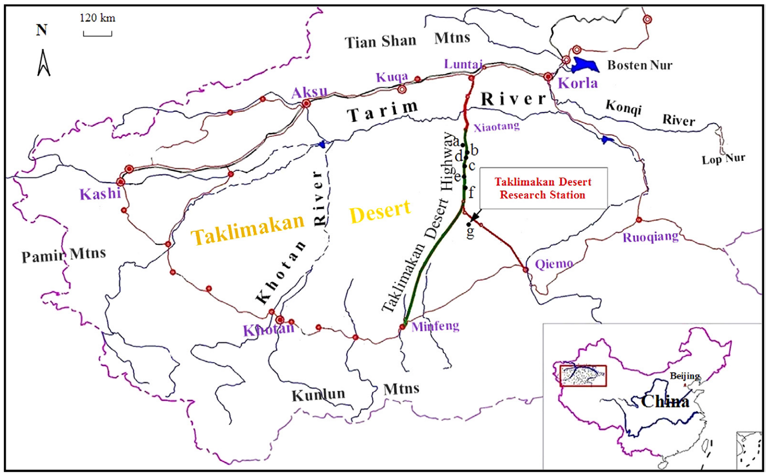

Fig. 1. Map showing of the Taklimakan Desert Highway and the monitoring sites. (The desert highway transects the Taklimakan Desert from Luntai (0 km) to Minfeng (522 km). The green line represents the artificial shelterbelt on both sides of the highway, and the seven black dots (a–g) represent the monitoring sites.)

Table 1. Physical and chemical properties of shifting sandy soil at the study area.

				Particle composition (%)			
pH (1:5)	EC (dS/m)	TSC (g/kg)	BD (g/cm^3)	Clay (<0.002 mm)	Silt (0.002–0.02 mm)	Fine sand (0.02–0.2 mm)	Course sand (0.2–2 mm)
8.26	0.437	1.31	1.49	0.28	12.35	82.83	4.54

Note: EC, electrical conductivity; TSC, total salt content; BD, bulk density.

et al. 2008*a*). The soil physiochemical properties are shown in Table 1 and the chemical properties of groundwater at selected monitoring sites along the TDHS are shown in Table 2.

The vegetation for most sections of the TDHS consists of *Calligonum aborescens, Tamarix ramosissima*, and *Haloxylon ammodendron* plant species (Fig. 2). These three species represent the majority of plant species that have been previously planted within the TDHS and, thus, are the focus of our current research. There are only very limited sections that have been planted with *Nitraria tangutorum*, *Populus euphratica*, and *Elaeagnus angustifolia* species. *Calligonum aborescens* was planted at the outer margin of the shelterbelt and is located farthest from the highway. The three species were interspersed along rows with a 2-m row spacing and a plant spacing of 1 m within the same row.

Table 2. Chemical properties of the drip-irrigated groundwater of selected sites along TDHS.

				Ions composition (g/L)					
Serial number	Location along TDHS (km)	Salinity (g/L)	pH	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+ & Na^+
a	122.99	29.70	7.80	0.23	12.18	5.99	0.76	1.08	9.43
b	148.80	20.99	7.58	0.19	8.97	4.85	0.69	0.83	5.40
c	176.00	13.99	8.02	0.04	5.13	3.98	0.31	0.48	4.03
d	155.80	10.00	8.02	0.09	4.37	2.14	0.24	0.31	2.84
e	201.10	4.82	7.85	0.07	1.80	1.07	0.10	0.25	1.52
f	255.20	2.82	7.40	0.06	1.07	0.69	0.07	0.09	0.83
g	TDRS	4.04	7.76	0.08	1.50	1.01	0.11	0.15	1.07

Note: TDRS = the Taklimakan Desert Research Station, shown in Fig. 1, and there is one special highway that connects it with the Taklimakan Desert Highway.

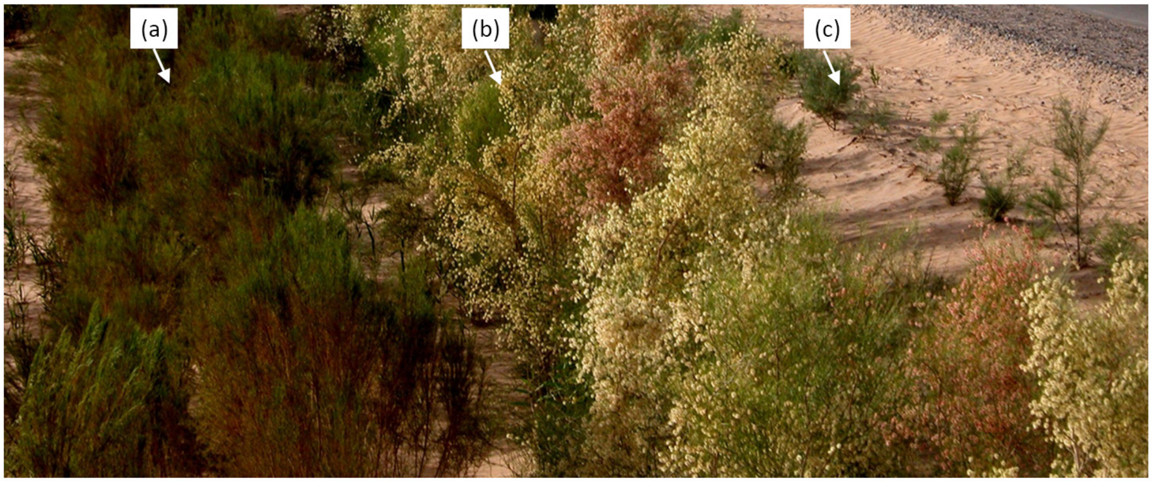

Fig. 2. Three main species in the shelterbelt planted for 1 yr (partial, taken by Xinwen Xu). (a) *Calligonum aborescens,* (b) *Haloxylon ammodendron,* (c) *Tamarix ramosissima.*

All the plants are drip-irrigated with local highly saline groundwater having a salinity of 2.82–29.87 g/L. The irrigation interval is typically 15 d in March, April, May, September, and October and 10 d in June, July, and August. The irrigation application rate is typically 30 L per plant per irrigation event (Xu et al. 2006). Shifting sand was stabilized after the construction of the TDHS and the long-term drip irrigation resulted in the formation of a salt crust that is widely distributed at the soil surface within the shelterbelt (Zhang et al. 2008*a*).

Experimental design

This paper presents an analysis of (1) seedling survival and growth as a function of water salinity, which were monitored over 10 yr along the whole shelterbelts, and (2) plant growth dynamics as a function of time, which was monitored over experimental plots at the Taklimakan Desert Research Station (TDRS, Fig. 1).

Response of seedling survival and height to irrigation water salinity

Field monitoring along the TDHS was conducted in September during planting years of 2003 to 2012. Six monitoring sites with different groundwater salinities (i.e. 2.82, 4.82, 10, 13.99, 20.99, and 29.7 g/L) were selected to investigate seedling survival. Each monitoring site extended 4 km in length irrigated by the pumped well along the TDHS within the shelterbelt and was 72–78 m in width. Seedling survival of the three common shrub species planted at selected monitoring plots was assessed by counting the number of living plants 6 months after establishment in March. Our experiment included data collected from more than 400, 000 seedlings. Each groundwater salinity treatment included 65 000 to 70 000 plants that covered both sides of a 4-km distance along the TDHS. Dead seedlings were replaced the following March to maintain a homogeneous plant density, and these replacement plants were not used in our analysis. Soil samples were obtained at depths of 0–10, 10–30, 30–50, 50–70, 70–90, 90–110, 110–130, and 130–150 cm located at five positions within each of the monitoring sites. These five positions were randomly selected between two adjacent plant rows that extended the 4-km length of the monitoring site. The two adjacent plant rows were located in the middle of the shelterbelt. Electrical conductivity (EC, soil:water = 1:5) of the soil was assessed using a temperature-conductivity meter (ZKNT-SY-3; Centrwin Technology Co., Ltd., Beijing, China).

Plants growth dynamics in the TDRS

In addition to our six monitoring sites, 10 plants of each species were drip-irrigated with water having a salinity of 4.04 g/L in the TDRS. These plants were evaluated for height, crown width, and maximum width of the basal stem in September after 2, 3, 4, 6, 8, and 9 yr of being planted in the afforestation process. Plant height and horizontal crown width in the east–west and south–north directions were measured using a ruler. Crown width was calculated using the following equation (Fu et al. 2013):

$$\mathrm{CW} = \frac{1}{4}\pi ab \qquad (1)$$

where CW (cm^2) is the crown width and a (cm) and b (cm) are the maximum horizontal crown lengths in the east–west and south–north directions, respectively. Maximum width of the basal stem diameter at the sand surface was measured using a vernier caliper.

The root distribution was measured in September after 1, 4, 7, and 9 yr of being planted in the afforestation process. Mean root distribution was assessed as an average of four plants of every species at the four ages. To reduce injury and protect plants when investigating the root distribution, a soil column was excavated in a 1 × 1 m quadrat on the southeast side of the plant until no roots were observed. The roots were collected at vertical soil sampling intervals of 20 cm, washed with water, and dried for 10 h at 105°C. After drying, the root dry mass was determined by weight.

Results

Response of seedling survival and height to irrigation water salinity

In the TDHS, survival rates of *Calligonum aborescens* and *Tamarix ramosissima* decreased with increased irrigation water salinity. The survival rate of *Haloxylon ammodendron*, however, initially increased and then decreased with an increase in irrigation water salinity (Fig. 3). The survival of *Haloxylon ammodendron* seedlings was >95% when irrigated with water having a salinity of 4.82 g/L. The survival rates of *Haloxylon ammodendron* seedlings under other salinities were a little lower, but more than 85% of the plants survived under all salinities of irrigation water within the first year after planting. Furthermore, the survival rate was reduced with increasing salinity of irrigation water when the salinity was greater than 4.82 g/L. Indications are that some salt stress can be beneficial to the survival of *Haloxylon ammodendron* seedlings.

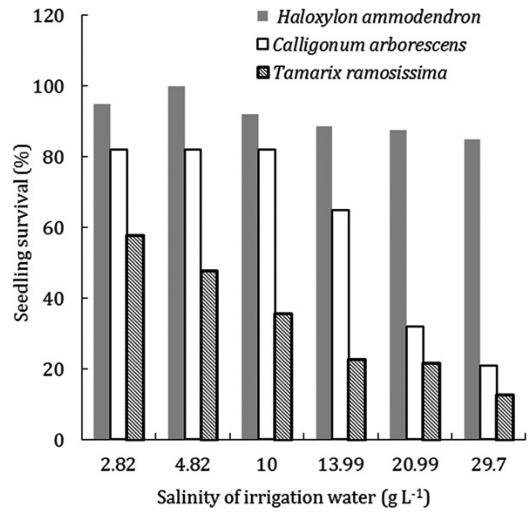

Fig. 3. Survival of three plant species drip-irrigated with groundwater of different salinity in TDHS.

The survival rates of *Calligonum aborescens* was nearly 80% when irrigated with water having a salinity of 2.82, 4.82, or 10 g/L, but was about 65% when irrigated with water having a salinity of 13.99 g/L. The survival rates were less than 50% when irrigating with water having a salinity of 20.99 or 29.7 g/L. Survival rates of *Tamarix ramosissima* were the lowest of the three species at all salinity levels of irrigation when compared with the other two species. Survival rates of *Tamarix ramosissima* were greater than 50% only when irrigated with water having a salinity of 2.82 or 4.82 g/L.

These results indicate that *Haloxylon ammodendron* was more tolerant of saline water than the other two species and that water having a salinity of 4.82 g/L was the most suitable for *Haloxylon ammodendron*. Water having a salinity of >13.99 g/L was not suitable for irrigation of *Calligonum aborescens* and water with a salinity >4.82 g/L was not suitable to irrigate *Tamarix ramosissima*.

After one growing season, the heights of *Calligonum aborescens* plants increased with lower salinity levels of irrigation water, and these plants were the tallest among the three species when irrigated with water having a salinity of ≤13.99 g/L (Fig. 4). The height of *Haloxylon ammodendron* initially increased and then decreased with irrigation water salinity. The *Haloxylon ammodendron* plants were tallest when irrigated with

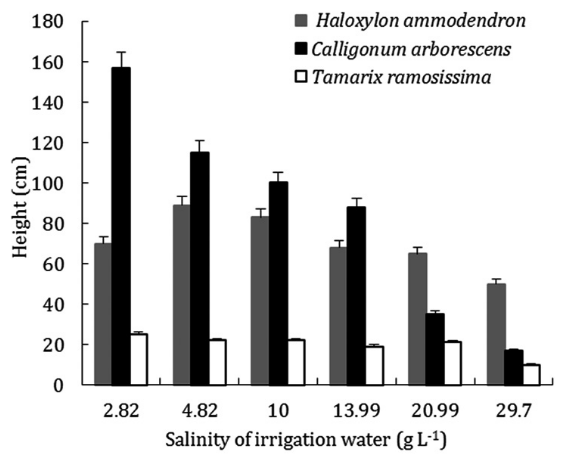

Fig. 4. Heights of the three species of plant seedlings after the first season of growth under drip irrigation of different salinities.

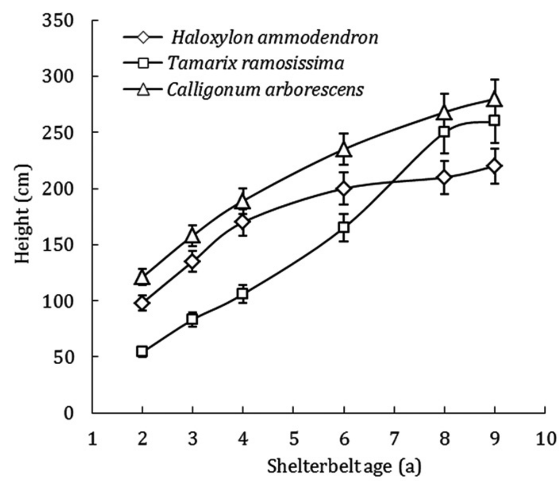

Fig. 5. Height dynamics of three plant species drip-irrigated with a salinity of 4.04 g/L. The vertical bars indicate 95% confidence intervals.

water having a salinity of 4.82 g/L. These results suggest that not only the rate of survival but also the heights of *Haloxylon ammodendron* plants performed the best among the observed salinities of irrigation water. The heights were lower for *Tamarix ramosissima* plants than the other two species using irrigation water of the same salinity. In addition, the heights of *Tamarix ramosissima* plants were not influenced by the salinities of irrigation water when the plant heights were <30 cm.

Plants growth with time

Plant height.—Fig. 5 shows the temporal variations in plant heights of the three species over 9 yr when irrigated with irrigation water having a salinity of 4.04 g/L. The heights of the *Calligonum aborescens* plants always seemed to grow at a stable rate, and this species of plants always had the greatest heights of the three species during the 9-yr monitoring period. *Calligonum aborescens* plants attained a height of approximately 120 cm during the 2nd yr, and the heights reached to more than 270 cm during the 9th yr. The rate of *Haloxylon ammodendron* plant growth was greatest during the first 4 yr and then slowed for the remaining 5 yr. The rate of *Tamarix ramosissima* plant growth was stable for the first 8 yr and then slowed during the last year. *Haloxylon ammodendron* plants were taller than *Tamarix ramosissima* plants during the first 6 yr, but were shorter during the last 3 yr.

During the 9 yr of this study, we discovered that *Haloxylon ammodendron* plants and *Calligonum aborescens* plants developed more lateral branches than *Tamarix ramosissima* plants. An increased number of lateral branches would have decreased the ventilation coefficient (Wang et al. 2005), thus an increased number of lateral branches was beneficial in controlling the movement of eolian sand near the surface (Zu et al. 2008, Khosronejad and Sotiropoulos 2014). These results suggested that *Haloxylon ammodendron* and *Calligonum aborescens* may be more beneficial in controlling mobile sand dunes after planting because of their faster growth and increased number of lateral branches.

Crown width.—Crown widths significantly varied among the three species during the 9 yr of the study (Fig. 6). Crown widths of the three species increased faster during the first 6 yr after planting, and then the crown widths increased at slower rates during the 7th and 8th yr. The crown widths surprisingly and suddenly increased during the 9th yr. It is hypothesized that as the rate of height growth slowed during the 9th yr, there was more dry matter accumulation that resulted in increased crown growth. According to the Taklimakan Desert Weather Station, there was also increased precipitation during the 9th yr that would be expected to result in increased growth of the crown width. *Calligonum aborescens* plants had the largest crown widths among the

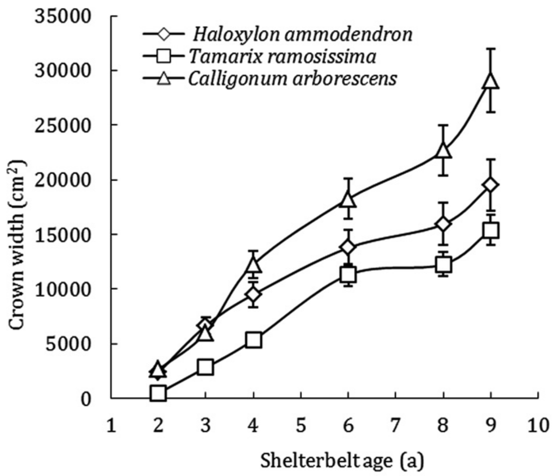

Fig. 6. Crown width growth dynamics of the three plant species drip-irrigated with a salinity of 4.04 g/L. The vertical bars indicate 95% confidence intervals.

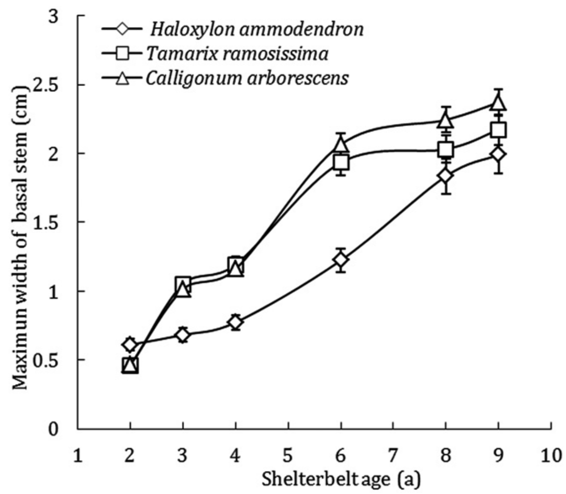

Fig. 7. Maximum widths of basal stem dynamics for the three plant species drip-irrigated with a salinity of 4.04 g/L. The vertical bars indicate 95% confidence intervals.

three species with values up to nearly 3 m^2. The *Haloxylon ammodendron* plants attained crown width values up to 1.9 m^2, while the crown width of *Tamarix ramosissima* plants attained values up to 1.5 m^2. Crown width is typically more important than height in reducing wind speed and controlling the movement of eolian sand (Bressolier and Thomas 1979), thus the larger crown width of *Calligonum aborescens* may be more beneficial in controlling sand movement.

Maximum width of basal stem.—During the 9 yr of this study, the maximum widths of the basal stems of *Calligonum aborescens* plants were generally larger than either *Haloxylon ammodendron* or *Tamarix ramosissima* plants. An exception to this general statement occurred during the 2nd yr of the study for *Haloxylon ammodendron* plants that were a little larger than the other two species (Fig. 7). *Calligonum aborescens* and *Tamarix ramosissima* plants showed similar growth dynamics in that plants of both species grew at an accelerated rate during the first 6 yr and at an obviously reduced growth rate during the latter 3 yr. It should be noted that *Calligonum aborescens* plants grew faster than *Tamarix ramosissima* plants starting during the 4th yr and that *Haloxylon ammodendron* plants grew at a reduced rate during the first 4 yr than during the latter 5 yr.

Roots growth.—Temporal trends in the vertical distributions of roots of the three species are presented in Fig. 8. The roots of the three species displayed a similar distribution pattern with a root mass that increased with increased soil depth from the surface to the 40-cm depth and then the root mass decreased as the soil depth increased from 40 to 100 cm. The root masses for all three species also showed increased growth with the shelterbelt age. For *Calligonum aborescens* planted for 1, 4, 7, and 9 yr, the maximum quantity of roots were measured in the 20–40 cm, 40–60 cm, 40–60 cm, and 60–80 cm soil layers, respectively. No roots were observed below a 120-cm soil depth when the plants were less than 7 yr in age. No roots were observed below an 80-cm soil depth for seedlings planted for 1 yr. Approximately 90% of roots existed in the 0–120 cm soil layer of *Calligonum aborescens* that had been planted for 9 yr.

The roots for *Haloxylon ammodendron* plants that were 1 yr in age were primarily observed in the 20–40 cm soil depth with approximately 92% in the 20–60 cm soil layer and no roots were observed below the 80-cm soil depth. When the *Haloxylon ammodendron* plants were 4 yr in age, the roots were primarily distributed in the 40–60 cm soil layer with approximately 89% distributed in the 0–100 cm soil layer. When the *Haloxylon ammodendron* plants were 7 yr in age, approximately 30% of the roots were observed

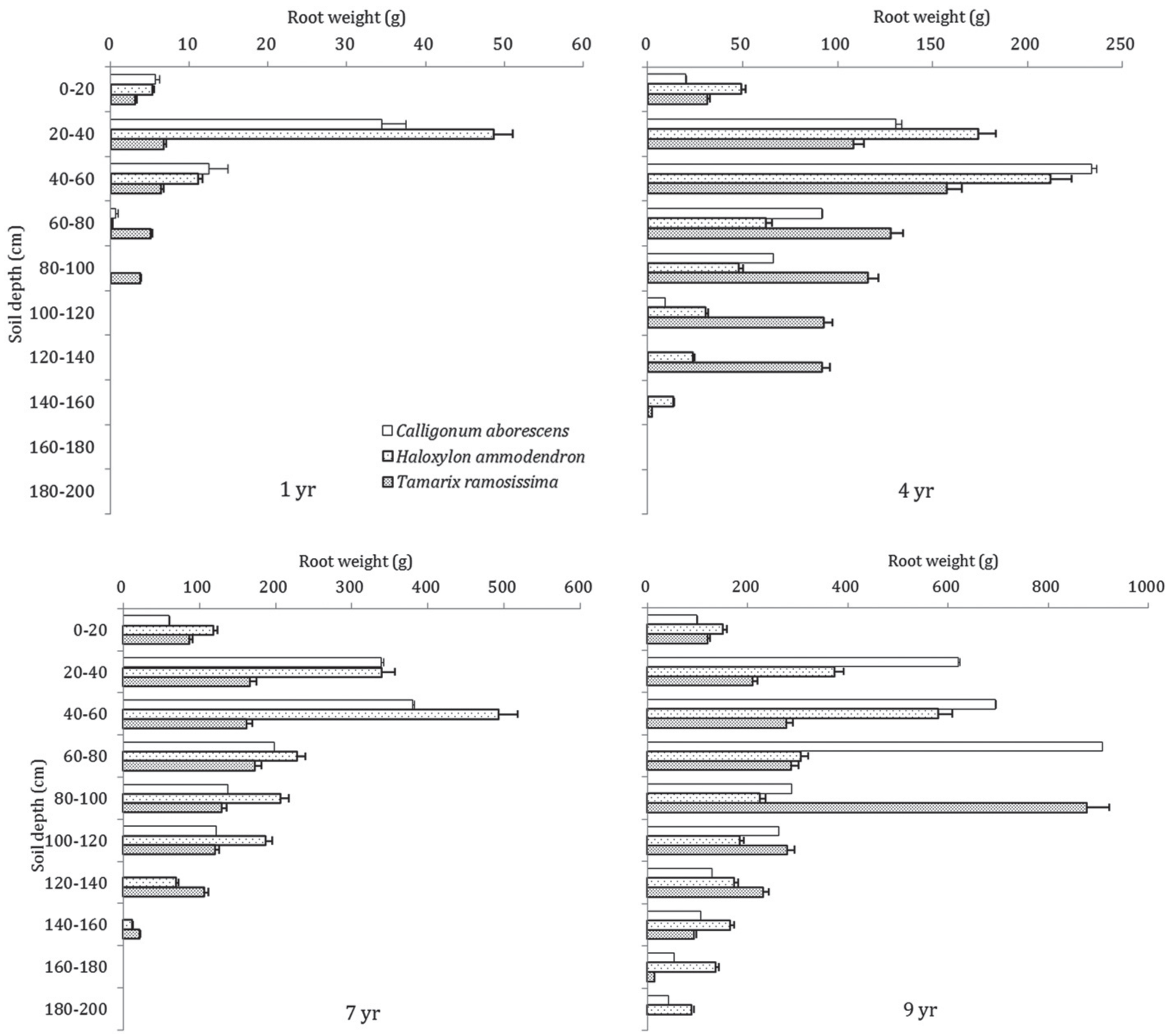

Fig. 8. Vertical distribution of roots for the three plant species that had been seeded for 1, 4, 7, and 9 yr within the shelterbelt and grown drip-irrigated with a salinity of 4.04 g/L. The horizontal bars indicate 95% confidence intervals.

in the 40–60 cm soil layer and more than 95% were observed in the 0–120 cm soil layer. When the *Haloxylon ammodendron* plants were 9 yr in age, approximately 24% of the roots were distributed in the 40–60 cm soil layer with roots being present down to a 200-cm soil depth and no roots being observed below the 200-cm soil depth.

Compared to *Calligonum aborescens* and *Haloxylon ammodendron*, the total root weights of *Tamarix ramosissima* plants were much lower in the shelterbelt for plants that were 1 yr and 7 yr in age, but larger than the root weights for the other two species planted in the shelterbelt for 4 yr. For plants that were 9 yr in age, the root weights of *Tamarix ramosissima* plants had root weights that were intermediate to the other two species (Table 3). The roots weights of *Tamarix ramosissima* plants that were 1, 4, 7, and 9 yr in age were observed to be at maximum values for the 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm soil layers, respectively, and accounted for 27%, 22%, 18%, and 37% of the total roots, respectively, observed in the 0–100 cm soil layers. Roots were observed at a soil depth of 0–100 cm when the seedlings were planted

Table 3. Total root weights of *Calligonum aborescens*, *Haloxylon ammodendron*, and *Tamarix ramosissima* plants grown in a soil column (excavated in a 1 × 1 m quadrat on the southeast side of the plant until no roots were observed.) for 1, 4, 7, and 9 yr in the shelterbelt. Means followed by different letters within a same column are significantly different at $P < 0.05$ using Fisher's LSD.

	Total root weights of different shelterbelt age (g)			
Plant species	1 yr	4 yr	7 yr	9 yr
Calligonum aborescens	$53.23^{b} \pm 6.38$	$551.16^{a} \pm 26.20$	$1236.94^{b} \pm 133.06$	$3202.50^{b} \pm 150.10$
Haloxylon ammodendron	$65.25^{c} \pm 5.42$	$614.47^{b} \pm 30.23$	$1654.84^{c} \pm 112.09$	$2387.02^{a} \pm 115.96$
Tamarix ramosissima	$24.83^{a} \pm 3.17$	$727.76^{c} \pm 98.04$	$968.09^{a} \pm 169.73$	$2393.42^{a} \pm 208.87$

for 1 yr, at a soil depth of 0–160 cm when the seedlings were planted for 4 and 7 yr, and at a soil depth of 0–180 cm when the seedlings were planted for 9 yr.

Discussion

Plants survival in response to high saline drip irrigation

Although plant species have different salt tolerances, plant age plays an important role in this sensitivity. Seedlings tend to be more sensitive to environmental stress than older plants. Thus, soil salinity in the root zone influences seedling survival (Li et al. 2014). The first year is crucial for the establishment of shelterbelt plants because the roots are primarily distributed within a shallow layer of soil that typically has a high salt content (Fig. 9). Our results showed that *Haloxylon ammodendron* plants have the highest salt tolerance, followed by *Calligonum aborescens* plants, and *Tamarix ramosissima* plants have the lowest salt tolerance. The use of higher salinity irrigation water introduces more salts into the soils and presents risks such as increased soil salinity (Zhang et al. 2008*a*), the occurrence of physiological drought, and increased risk of salt toxicity to plants (Rengasamy 2002, Zeng et al. 2008, Schachtsiek et al. 2014, Sperling et al. 2014). This study demonstrated that the soil salinity of different soil depths increased with irrigation water salinity, and that the shallow soils had higher salinities (Fig. 9). In general, increasing mortality was observed with the increased salinity of irrigation groundwater. However, these levels of increased salinity significantly affected *Calligonum aborescens* and *Tamarix ramosissima* plants while the *Haloxylon ammodendron* plants were not significantly affected. *Haloxylon ammodendron* is one of the dilute salt halophytes, which can tolerate high saline soil environments (Zhao and Fan 2005), and its most suitable growth conditions does not favor freshwater irrigation.

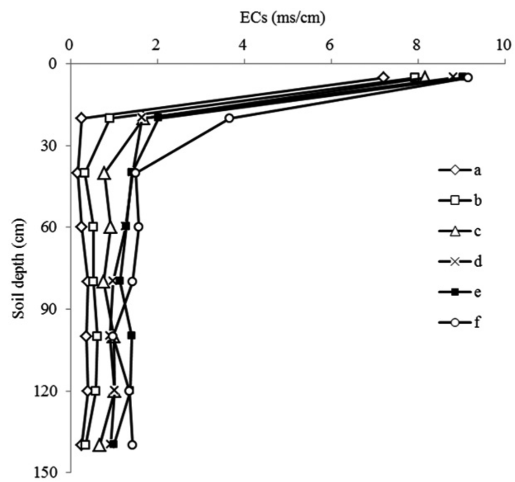

Fig. 9. Soil salinity vertical distribution within soil under drip irrigation with different groundwater salinities. ECs = soil electrical conductivity; a = 2.82 g/L, b = 4.82 g/L, c = 10 g/L, d = 13.99 g/L, e = 20.99 g/L, and f = 29.7 g/L.

Plant adaptation to saline drip irrigation and extreme arid environment

The three species observed in this study grew well under saline drip irrigation with groundwater having a salinity of 4.04 g/L. The growth and development of plants occurs as a result of photosynthesis, thus high salt stress may result in the reduction of the chlorophyll levels. Plants must be able to photosynthesize to survive under stress conditions (Strongonov 1973). It is reported that the chlorophyll contents of three plants in the TDHS decreased with increased irrigation salinity (Xu et al. 2008), which would be expected to reduce photosynthesis. Therefore, lower photosynthesis and more energy consumption resulted in the growth reduction of plant the above- and below-ground plant biomass. With increased plant age within the shelterbelt, the plants grew stronger, their roots distributions were deeper and wider into the soil which would be expected to strengthen their moisture absorption. Increased moisture adsorption is the plants' main adaption mechanism to droughty soil environments (Wang et al. 2008). Irrigation produces a better soil moisture environment, but it has been shown to not always be beneficial for root development and expansion. The three species used in this study have been shown to have deeper and wider root distributions under natural arid environments (Li 1996, Xu and Li 2009, Zeng et al. 2010) when compared to the root distributions in our artificial irrigation condition.

As shown in Fig. 9, even though plants were irrigated with high saline water, soil beneath the 20-cm depth had rather low salt contents because of high levels of evaporation (Zhang et al. 2008*a*). The roots of shelterbelt plants are primarily distributed within the wetting zone of the soil profile and thus the reason the plants grow well in TDHS. Our results support the findings of Li (1996) that *Calligonum aborescens* has horizontal and shallow root distribution, and that their distribution is influenced by irrigation and soil moisture distribution (Dhief et al. 2011). However, because the root distributions of the three plant species are different and the plants are grown in mixed cultures with the two other species, the competition for moisture is not extreme. This lack of competition for moisture results in utilizing soil moisture at different depths. Thus, the difference in root distribution at different soil depths is one reason for using this mixture of plants in TDHS. The soil moisture has been shown to be sufficient for the plants' physiological needs under the current irrigation schedule (Wang et al. 2008). With increased shelterbelt age, the roots distribution range will increase and should result in an improved soil moisture utility range and efficiency, and the plants' salt tolerance and drought-resistance would be strengthened.

Implications for afforestation in arid shifting deserts with saline irrigation

In this study, the seedling survival of three species of commonly grown shelterbelt plants was significantly affected by irrigation water salinity. Soils can influence plant survival and growth, and plants promote the healthy development of the soil. This synergy is very important in developing sustainable management systems. More mature shelterbelts have better soil fertility, more biodiversity, and reduced salinity. Thus, more mature shelterbelts may be beneficial for plant growth and sustainability (Jin et al. 2008, Zhang et al. 2008*b*). Water consumption, however, increases as plants mature (Xu et al. 2008) thus irrigation amounts will gradually increase with shelterbelt age. Alternately, if the groundwater level is less than 2 m, the plants can be considered to be unirrigated or would require less irrigation resulting in reduced water use and reduced maintenance cost (Li et al. 2013).

Not only in the Taklimakan Desert but also in many degraded drylands and shifting sandy lands, afforestation has great significance to reduce soil erosion, lower the risk of salinization, and improve soil nutrient levels (Danso et al. 1992, Jin et al. 2008, Lei et al. 2008*b*, Jiao et al. 2010, Yin et al. 2010). On the contrary, these positive effects of afforestation will inevitably result in improved plant growth, which are necessary conditions for the sustainable development of artificial forests (Chigani et al. 2012). Meanwhile, more suitable plants should be selected, and more sustainable technologies should be developed in this area and other analogous regions in the world.

It is known that an artificial ecosystem meets all the criteria of a natural ecosystem, but the artificial ecosystem is created and controlled by humans. Artificial ecosystems are created to mimic natural ecosystems, but are often less complex in the extent of plant species with a very low genetic diversity. Urban sprawl, population growth, and exploration of resources have destroyed numerous natural ecosystems around the world. The expansion of artificial ecosystems plays an important role in the development and maintenance of future global ecosystems. As an artificial ecosystem, the main purpose of constructing the TDHS was to protect the highway from shifting sand disasters. However, after its construction, the biodiversity in this ecosystem has increased over time (Zhang et al. 2011). Biodiversity has been shown to play an important role in CO_2 fixation (Zhang et al. 2008*b*). Thus, developing sustainable artificial ecosystems at low costs should be the focus of future research.

Conclusions

Our findings generally support the concept that afforestation using drip irrigation of highly saline groundwater within extreme arid shifting desert regions is feasible, and *Calligonum aborescens* plants should be grown at the outer margin of the shelterbelt due to its faster growth to more quickly stabilize the shifting sand. However, there have been insufficient studies to identify a range of plant species that can be used and adapted for the specified conditions. Saving water and improving water use efficiency are certainly important issues associated with such drought regions to avoid lowering the groundwater levels and preventing the regional ecological degradation of the shelterbelt environment. There also needs to be additional studies conducted for increasing the sustainable development of these shelterbelt areas.

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