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RESEARCH ARTICLE

Varying water utilization of *Haloxylon ammodendron* plantations in a desert-oasis ecotone

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Abstract

Haloxylon ammodendron is a desert shrub used extensively in China for restoring degraded dry lands. An understanding of the water source used by *H. ammodendron* plantations is critical achieving sustainable vegetation restoration. We measured mortality, shoot size, and rooting depth in 5-, 10-, 20-, and 40-year-old *H. ammodendron* plantations. We examined stable isotopic ratios of oxygen ($\delta^{18}O$) in precipitation, groundwater, and soil water in different soil layers and seasons, and in plant stem water to determine water sources at different shrub ages. We found that water acquisition patterns in *H. ammodendron* plantations differed with plantation age and season. Thus, the main water source for 5-year-old shrubs was shallow soil water. Water sources of 10-year-old shrubs shifted depending on the soil water conditions during the season. Although their tap roots could absorb deep soil water, the plantation main water sources were from soil water, and about 50% of water originated from shallow and mid soil. This pattern might occur because main water sources in these plantations were changeable over time. The 20- and 40-year-old shrubs acquired water mainly from permanent groundwater. We conclude that the main water source of a young *H. ammodendron* plantation was soil water recharged by precipitation. However, when roots reached sufficient depth, water originated mainly from the deep soil water, especially in the dry season. The deeply rooted 20- and 40-year-old shrubs have the ability to exploit a deep and reliable water source. To achieve sustainability in these plantations, we recommend a reduction in the initial density of *H. ammodendron* in the desert-oasis ecotone to decelerate the consumption of shallow soil water during plantation establishment.

KEYWORDS

groundwater table, *H. ammodendron* root depth, oxygen stable isotope, precipitation pulse, water use pattern

1 | INTRODUCTION

Haloxylon ammodendron, as a typical desert plant, has physiological and morphological traits that allow it to survive frequent aridity, torridity, and other environmental stresses (Xu & Li, 2006, Buras et al., 2012), native to desert ecosystems of central Asia, typically found on sand dunes in desert habitats with average annual rainfall ranging from 30 to 200 mm (Zou, Li, Xu, & Xu, 2010; Su, 2010). Natural stands and plantations of this shrub exhibit forest stand structure with plant cover reaching more than 50% (Zhang, Chen, Zhao, & Li, 2010). *H. ammodendron* plays a significant role in the maintenance of structure and ecological function of desert ecosystems, and it decreases wind speed, intercepts drifting sand, and reduces air temperature (Jia, Ji, Ning, & Liang, 2008). For this reason, *H. ammodendron* plantations facilitate the stabilization of active sand dunes. However, lack of quantitative research on its water sources is mainly due to the unpredictable nature of precipitation and the complexity of its function.

The plain oasis in the middle of the Heihe River Basin has become an important source of grains in China. Crop water requirements were supplied mainly by irrigation from the Heihe River and groundwater (Zhao et al., 2011; Liu et al., 2010). However, the irrational reclamation of land and over-utilization of natural resources in oases led to deterioration in oasis environments. Starting in the mid-1970s, sand-stabilizing *H. ammodendron* forests have been established on desertified sandy lands in the Linze desert-oasis ecotone part of the mid-Heihe River system. However, establishment of *H. ammodendron* plantations in extremely arid areas is inconsistent with its biological zonality (Walter, 1973), because the low and highly variable precipitation (annual precipitation <150 mm with 75% occurring in summer) cannot support the growth and development of *H. ammodendron*. Thus, sources of water became the main concern for sustainable forest development and ecosystem restoration in the desert-oasis ecotone.

Zhu, Kang, Tan, and Xu (2006) and Zeng, Hu, Chang, and Fan (2009) found that large-scale monospecific plantations do not follow succession climax on a regional scale. Establishment of monospecific *H. ammodendron* forests is a main ecological restoration practice for the arid desert regions in China, but the stands at the current planting densities are unsustainable due to low and variable precipitation. In fact, soil water content (SWC) significantly decreased, and shrub mortality began prior to age 5 and increased with stand age (Ma, Wang, & Zhu, 2007a; Zhu & Jia, 2011). Young *H. ammodendron* plantations cannot utilize groundwater because it resides too deep for the developing root system. On the other hand, the mean annual precipitation was less than 150 mm with uneven distribution during the growing season. As shrubs mature, the plantations need increasingly more water, and limited water resources lead to plantation degradation (Ma et al., 2007a; Jia et al., 2008; Zhu et al. 2011; Wang, Zhao, Liu, Zhang, & Li, 2015). In order to avoid drought stress, roots of maturing *H. ammodendron* gradually penetrate deeper into the soil profile to use groundwater (Xu & Li, 2008; Dai, Zheng, Tang, & Li, 2014).

Stable isotopes provide a powerful tool for unraveling the movement of water through ecosystems (Kendall & McDonnell, 1998), and plant water sources can be determined by comparing the stable isotope ratios (of hydrogen and oxygen) of all potential water sources with those of water extracted from the plant stem (Ehleringer & Dawson, 1992; Dawson, Mambelli, Plamboeck, Templer, & Tu, 2002; Song, Zhu, Li, & Yu, 2014). The stable isotope values of oxygen and hydrogen in water can be applied to water-acquisition studies because they generally do not change during water uptake (there is no isotope fractionation) by terrestrial plants (Mensforth, Thorburn, Tyerman, & Walker, 1994; Dawson et al., 2002); however, some halophytic or xerophytic plant species seem to fractionate H (but not O) during water uptake (Lin & Sternberg, 1993; Ellsworth & Williams, 2007). Thus, stable isotope ratios (δ^{18}O) of water derived from plant stems are likely to reflect water sources that the particular plant uses (Jackson et al., 1999; Grieu, Lucero, Ardiani, & Ehleringer, 2001). Therefore, comparisons of stable isotopic compositions of stem water with those of the potential water sources (e.g., soil water from varying depths, precipitation, river water, and groundwater) could identify the most probable sources of water transpired by plants (Brunel, Walker, & Kennett-Smith, 1995; Asbjornsen, Mora, & Helmers, 2007; Li et al., 2007). In addition, linear mixing models and the software IsoSource can identify the fractional contribution of each potential water source to plant water balance based on mass balance equations (Phillips & Gregg, 2001, Phillips & Gregg, 2003; Phillips, Newsome, & Gregg, 2005).

H. ammodendron exhibits a tree-life form, growing as a large shrub, depending on the age and environment; it exhibits a C_4 photosynthetic pathway and has deep root systems, which allow it to reach groundwater (Xu & Li, 2008; Zou et al., 2010). The species' physiological activity, individual morphology, and even long-term adaptive strategy are influenced by precipitation patterns (Xu & Li, 2006; Xu, Li, Xu, & Zou, 2007). Climate change models indicate that variability in precipitation will be increasing significantly over the next 20 years in the extensive arid region of Central Asia (Xu & Wei, 2004). Further, groundwater table will decrease because of overexploitation in nearby oases (Su et al., 2007a; Wang & Zhao, 2015). Given the potential for increased variability in precipitation, and the growing efforts at ecosystem restoration with *H. ammodendron* forests, the objectives of our study were to understand the shrub use of seasonal precipitation inputs and of groundwater, and how this use changes with increasing rooting depth as shrubs age. This study tested two hypotheses addressing water use by *H. ammodendron* plantations in desert habitats: (a) The source of water changes seasonally for shrubs with different rooting depths at different ages and (b) shrub access to a stable water resource such as groundwater makes *H. ammodendron* plantations less affected by fluctuations in precipitation.

2 | MATERIALS AND METHODS

2.1 | Study sites and experimental design

This study was conducted in a plantation of *H. ammodendron*, near the Linze Inland River Basin Research Stations, Chinese Academy of Sciences (39 °21′N, 100 °07′E, 1,374 m a.s.l.), located in a typical desert-oasis ecotone at the southern edge of the Badain Jaran Desert (Figure 1). The area has arid temperate climate zone. The mean annual temperature is 7.6 °C, mean annual precipitation is 116.8 mm (1965–2000), and over 80% of precipitation occurs between May and September. Mean annual open-water evaporation is 2,390 mm, mean annual wind velocity is 3.2 m/s, and prevailing wind direction is northwest. Gales with wind velocity >17 m/s occur 15 or more days/year (Su et al., 2007a). Soils are characterized by coarse texture and loose structure and are very susceptible to wind erosion. The textural composition is 89.52% sand, 5.97% silt, and 4.51% clay (Su et al., 2007a).

The study area is located at the fringe of the oasis, which has an agricultural development history of over 2,000 years owing to its flat land, adequate sunlight, and convenient water resource from the Qilian Mountains. However, desertification around the oasis margin developed rapidly during the second half of the 20th century and reached a climax in the mid-1970s. During the peak of desertification, Lanzhou Institute of Desert Research, Chinese Academy of Sciences, conducted a desertification control project to restore vegetation and rehabilitate desertified land (Su et al., 2007a). First, barriers composed of straw and reeds were placed on mobile dunes to protect against drifting sand, and then, seedlings of drought-tolerant desert shrub species, including *H. ammodendron*, were planted on sand dunes without irrigation. In this manner, a protection system was formed by enclosing farmland at the periphery of the oasis with *H. ammodendron* plantations. In the subsequent several years, similar projects were conducted in adjacent areas, and the area of shifting

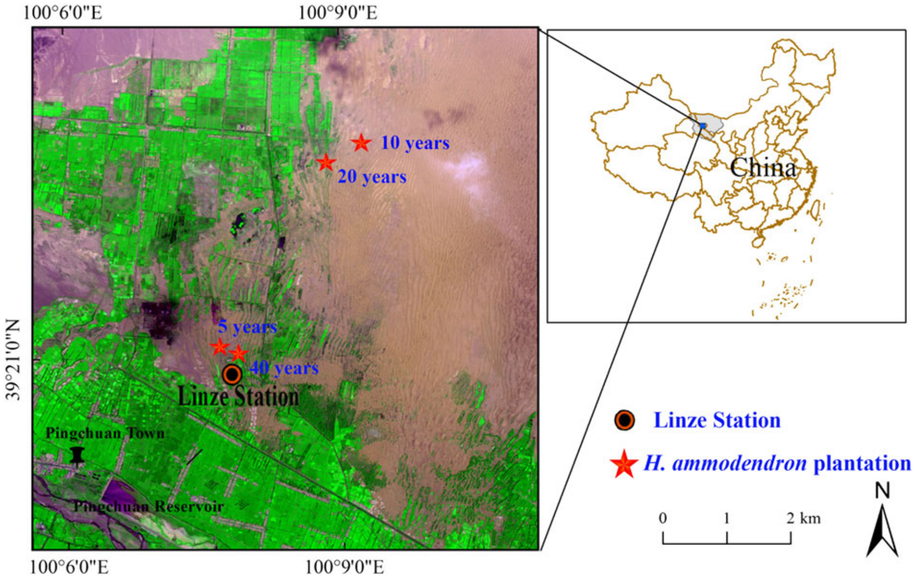

FIGURE 1 Location of the study sites in 5-, 10-, 20-, and 40-year-old *Haloxylon ammodendron* plantation

sands declined from 54.6% pre- to 9.4% post-treatment (Su, Wang, Zhang, & Du, 2007b).

A substitution method of "space" for "time" is normally considered a reliable way to monitor and study changes over long time periods (Sparling et al., 2003). The experimental sites established in different periods provided us with sufficient information to evaluate the eco-hydrological processes of planted *H. ammodendron* forest. One- year-old seedlings of *H. ammodendron* were manually planted in Su, 2010, 2005, 1995, and 1975 using single -stems in rows at about 2.0 m × 2.5 m spacing (Su, Wang, Zhang, & Du, 2007b). We established one plot (100 × 100 m) in each of 5-, 10-, 20-, and 40-year-old *H. ammodendron* plantation (one at each study site; Figure 1). We used a quadrat method to investigate the structure and quantitative characteristics of *H. ammodendron* plantation at each site; thus, we measured height, canopy radius, and basal diameter, and we counted the number of individuals in three quadrats (10 m × 10 m) per plot. We used the trenching method (Komiyama, Ogino, Aksornkoae, & Sabhasri, 1987) to investigate root depth. Trenches paralleled to the tree row at a distance of 10 cm. We defined the depth of the trench as the stand root maximum depth, taken when we did not find any roots at the bottom of the trench. Three trenches were made in each sampling plot in early August.

2.2 | Sample collection

Between April and October of 2014, plant and soil sampling was conducted in spring (April–May), summer (June–August), and autumn (September–October) to characterize seasonal water isotope signatures. At each site, three healthy shrubs with mean crown breadth were selected and tagged for the stable isotope ratios measurement. Five small twigs (diameter 0.2–0.5 cm and length 4–5 cm) were collected at the base of the live crown of each study plant at monthly intervals. The twigs were immediately decorticated and placed in glass vials sealed with a screw-lid and Parafilm wrap and placed in a cooler for transport to the laboratory. Samples were stored refrigerated until water extraction. At the same time as plant sampling, three replicates of soil samples were obtained with a hand auger from 0 to 300 cm depth near the canopy edge of each sampling plant. Soil samples from 0 to 100 cm depth were collected at 10-cm intervals, and those from 100 and 300 cm depth were collected at 20-cm intervals. Soil samples were separated into two parts for stable isotope analyses and for water-content determination. One subsample was immediately placed in plastic centrifuge tube sealed with a screw-lid and Parafilm wrap, placed in a cooler for transport to the laboratory, and refrigerated until water extraction; the other subsample was sealed in a tin cup and placed in a cooler for transport to the laboratory for measurements of SWC by the oven-drying method.

Precipitation amounts and temperatures in the study area were recorded by a weather station near the site. Precipitation samples were collected in six 300-ml beakers placed outdoors during almost all precipitation events. Groundwater observation wells were established previously for other research. We collected groundwater samples on each plant and soil sampling date. Both precipitation and groundwater samples were filtered using a 0.22-μm filter and immediately enclosed in glass vials, wrapped in Parafilm and refrigerated at 2 °C until stable isotope analysis.

In addition, we also collected three replicate samples of plants (same plants were sampled over time) and soils after precipitation events to investigate plant water use patterns during summer rainfalls. We tracked two typical precipitation events in summer. Plant twigs were collected 1, 2, 3, 5, and 8 days after a 24.8- (on DOY 203) and an 8-mm rainfall (on DOY 215). Additionally, three replicate samples of soil were collected at 10-cm depth intervals near the canopy edge of the study plants to investigate the isotopic values of soil water and SWC in the 0–100-cm layer. Plant samples were immediately placed in glass vials sealed with a screw-lid and Parafilm wrap and transported in a cooler to the laboratory; soil samples were immediately placed in plastic centrifuge tubes sealed with a screw-lid and Parafilm wrap, transported in a cooler to the laboratory, and refrigerated until water extraction.

2.3 | Isotopic analyses

Plant and soil water was extracted by cryogenic vacuum distillation (Ehleringer, Roden, & Dawson, 2000), and extracted water samples were stored in sealed glass vials at 2 °C. All water samples were measured for their oxygen isotopic composition in an isotope ratio infrared spectroscopy analyzer—the liquid water isotope analyzer (912-0008-1001, Los Gatos Research Inc., Mountain View, CA, USA)—with repeatability/precision ($\delta^{18}O$) of 0.1‰. Isotope ratio infrared spectroscopy-extracted stem water of some species may contain compounds that interfere with accurate isotope ratio measurements; these potential contaminants were identified and quantified with the spectral contamination identifier (liquid water isotope analyzer) post-processing software, and the isotope values of contaminated water samples were corrected (Schultz, Griffis, Lee, & Baker, 2011). For details of the procedure, see Wu, Zhou, Zheng, Li, and Tang (2013). Because hydrogen isotopic fractionation has been observed, but oxygen isotopic fractionation is negligible during water uptake by certain halophytic or xerophytic plants (Lin & Sternberg, 1993; Ellsworth & Williams, 2007), we only used oxygen isotopes to determine plant water sources. The stable oxygen isotope values ($\delta^{18}O$) are expressed relative to an accepted standard (Vienna Standard Mean Ocean Water) on per mil (‰) basis:

$$\delta^{18}O = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1\right) \times 1000\%,$$

where R_{sample} and R_{standard} are the oxygen stable isotopic compositions (18O/16O molar ratio) of the sample and standard water (Standard Mean Ocean Water).

2.4 | Data analyses

Isotopic composition of stem water was compared with that of potential water sources (potential water sources tested: precipitation, shallow soil water (0–50 cm), mid-depth soil water (50–150 cm), deep soil water (150–300 cm), and groundwater). The potential water sources (0–50, 50–150, and 150–300 cm and groundwater) were identified as follows: (a) Shallow soil water (0–50 cm) was the most unstable zone where the $\delta^{18}O$ values and SWC varied significantly with season and depth, (b) middle soil water (50–150 cm) had lower $\delta^{18}O$ values than shallow soil water and only mild seasonal and deep changes, (c) deep soil water (150–300 cm) had relatively stable $\delta^{18}O$ values within the soil profile and did not show significant seasonal changes, and (d) groundwater had relatively constant $\delta^{18}O$ values. We used the IsoSource model to calculate the contribution of each source to stem water (Phillips & Gregg, 2003). We conducted multiple comparisons of $\delta^{18}O$ values for soil water from individual layers with a one-way analysis of variance and Fisher's least significant difference method. Independent-sample *t* tests were used to test for differences in $\delta^{18}O$ values in stem water of different-aged *H. ammodendron* plantations. Significance was determined at the 95% confidence level (a = 0.05). All statistical analyses were performed with SPSS software (version 17.0, SPSS Inc., Chicago, IL, USA).

3 | RESULTS

3.1 | Stand structure

Shoot size (height, basal diameter, and canopy area) and rooting depth of *H. ammodendron* shrubs increased during the four plantation age stages (5-, 10-, 20-, and 40-year old; Table 1). Based on the root depth, only 20- and 40-year-old shrubs could reach the water table; 10-year-old shrubs penetrated into the deep soil profile but could not reach the water table; and 5-year-old shrubs reached into the middle soil profile (Table 1). Mortality in the 40-year-old stand was only slightly greater than that in the 20-year-old stand, but mortality in the 20- and 40-year-old stands was more than twice as high as that in the 10-year-old stand. Mortality in the 10-year-old stand was also slightly greater than mortality in the 5-year-old stand.

3.2 | Seasonal changes in $\delta^{18}O$ in precipitation and in groundwater

In the study area, precipitation from April to October 2014 totaled 99.6 mm, accounting for 90% of annual precipitation that year; 85.8 mm of that amount fell during the summer months of June to August. Oxygen isotope ratios ($\delta^{18}O$) of rainwater varied significantly among precipitation events, ranging between −7.03‰ and 8.85‰ (Figure 2). The isotope ratio of summer precipitation exhibits a significant effect of precipitation amount (Dansgaard, 1964). In this study, the $\delta^{18}O$ values of rainwater were negatively correlated with precipitation amount (r = −.714, p = .045, n = 15). The mean $\delta^{18}O$ values of precipitation in spring (April–May) and autumn (September–October) were lower than those in summer (June–August; Table 2). The isotopic

TABLE 1 Characteristics (mean ± SD) of *Haloxylon ammodendron* plantations

Age	5-year-old	10-year-old	20-year-old	40-year-old
Height (m)	1.63 ± 0.04	1.85 ± 0.13	4.38 ± 0.30	5.15 ± 0.25
Basal diameter (cm)	3.3 ± 0.2	5.5 ± 0.3	18.6 ± 0.7	32.3 ± 2.9
Canopy area (m^2)	0.61 ± 0.04	2.70 ± 0.72	13.05 ± 0.95	22.53 ± 2.39
Root depth (m)	1.54 ± 0.38	2.65 ± 0.68	4.65 ± 0.58	4.88 ± 0.57
Stand density (individual/ha)	2,825 ± 18	2,253 ± 23	1,224 ± 25	685 ± 28
Mortality (individual/ha)	457 ± 22	724 ± 32	1,453 ± 41	1,862 ± 51
Proportion dry branches (%)	35.00 ± 13.19	41.00 ± 13.73	73.10 ± 17.52	53.90 ± 18.33
Vegetation coverage (%)	18.60 ± 2.52	43.20 ± 4.31	86.90 ± 5.38	83.40 ± 4.25
Groundwater table (m)	4.56 ± 0.52	4.80 ± 0.48	4.40 ± 0.44	4.56 ± 0.52

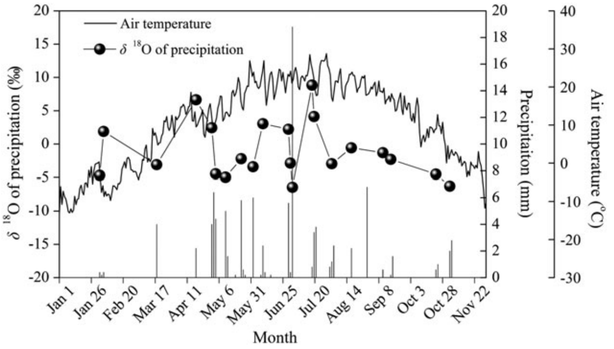

FIGURE 2 $\delta^{18}O$ values for rainwater and the corresponding precipitation event with the average daily temperature between April and October 2014

signature of groundwater varied little both in time and space, with the $\delta^{18}O$ values between −7.65 and −8.86. The groundwater was also isotopically depleted compared with the precipitation in Linze.

3.3 | Seasonal changes in SWC and in $\delta^{18}O$ in soil water and plant stem water

During the growing season of 2014, SWC varied significantly with season ($p < .001$) and soil depth ($p < .001$) at the four study sites (Figure 3 a–d). In the upper 50 cm of the soil profile, SWC increased significantly from spring to autumn following an increase in precipitation events; SWC at the 20-year-old site was significantly greater than that at other sites, especially in summer and autumn (Figure 3c). At 50–150-cm depth, SWC exhibited mild seasonal fluctuations and significantly increased with depth in all study sites. SWC below 150 cm increased with depth; at the 10-year-old site, this increase was dramatic due to a change in soil texture from sand to clay.

The $\delta^{18}O$ values of soil water at the four study sites varied with seasons and exhibited a monotonic decline from the soil surface to the water table (Figure 3e–f). The one-way analyses of variance indicated significant differences in $\delta^{18}O$ for both effects—soil layers

TABLE 2 Average $\delta^{18}O$ (‰) values (mean ± SD) for precipitation, shallow, mid-, and deep soil, and groundwater and stem water for 5-, 10-, 20-, and 40-year-old *Haloxylon ammodendron* plantation during the growing season

Sample	Age	Spring $\delta^{18}O$ (‰)	Summer $\delta^{18}O$ (‰)	Autumn $\delta^{18}O$ (‰)	*F*	*p*
Precipitation		−2.0 ± 5.8	0 ± 4.0	−3.6 ± 3.8	34.23	<.01
River water		−8.0 ± 0.1	−7.8 ± 0.2	−8.3 ± 0.1	2.32	.79
Shallow	5-year-old	1.4 ± 0.1	5.4 ± 0.8	4.9 ± 1.6	17.19	<.01
	10-year-old	1.8 ± 1.0	6.6 ± 2.2	5.9 ± 1.6	17.43	<.01
	20-year-old	2.4 ± 2.7	6.8 ± 0.2	6.5 ± 2.2	14.59	.01
	40-year-old	1.6 ± 0.1	5.5 ± 1.1	4.5 ± 2.0	18.14	<.01
	F	1.04	1.1	0.73		
	p	.43	.4	.56		
Mid-depth	5-year-old	−1.3 ± 0.2	−2.3 ± 0.2	−2.2 ± 0.1	21.94	<.01
	10-year-old	−1.3 ± 0.5	−0.3 ± 1.1	−1.2 ± 1.4	10.85	.04
	20-year-old	−2.2 ± 1.4	−0.3 ± 0.3	−0.5 ± 0.1	9.54	.03
	40-year-old	−1.0 ± 0.5	−2.3 ± 0.5	−2.3 ± 0.1	11.67	.01
	F	1.25	10.32	4.34		
	p	.35	<.01	.04		
Deep	5-year-old	−6.6 ± 0.2	−6.2 ± 0.2	−6.2 ± 0.1	4.8	.06
	10-year-old	−5.3 ± 0.1	−6.1 ± 0.3	−6.0 ± 0.4	0.87	.47
	20-year-old	−6.9 ± 0.7	−5.1 ± 0.2	−5.6 ± 0.1	6.23	.27
	40-year-old	−5.8 ± 0.5	−6.3 ± 0.2	−6.3 ± 0.2	2.29	.18
	F	3.1	2.89	5.07		
	p	.23	.15	.22		
Groundwater	5-year-old	−8.3 ± 0.7	−7.7 ± 0.8	−8.0 ± 0.4	1.25	.57
	10-year-old	−8.8 ± 0.2	−7.7 ± 0.4	−8.2 ± 0.6	2.06	.69
	20-year-old	−8.2 ± 0.8	−8.3 ± 0.6	−8.0 ± 0.3	3.12	.83
	40-year-old	−7.7 ± 0.2	−7.7 ± 0.6	−7.7 ± 0.8	1.25	.45
	F	2.36	0.129	1.11		
	p	.66	.24	.46		
Stem water	5-year-old	2.0 ± 0.6	2.9 ± 1.6	−3.2 ± 0.5	16.01	<.001
	10-year-old	−1.6 ± 2.7	−5.5 ± 0.3	−5.4 ± 0.3	13.04	<.001
	20-year-old	−6.1 ± 2.0	−7.9 ± 0.3	−6.4 ± 0.3	1.12	.39
	40-year-old	−7.3 ± 1.0	−7.2 ± 0.9	−7.8 ± 0.5	0.24	.8
	F	15.87	97.50	8.65		
	p	<.01	<.01	.01		

$p < .05$.

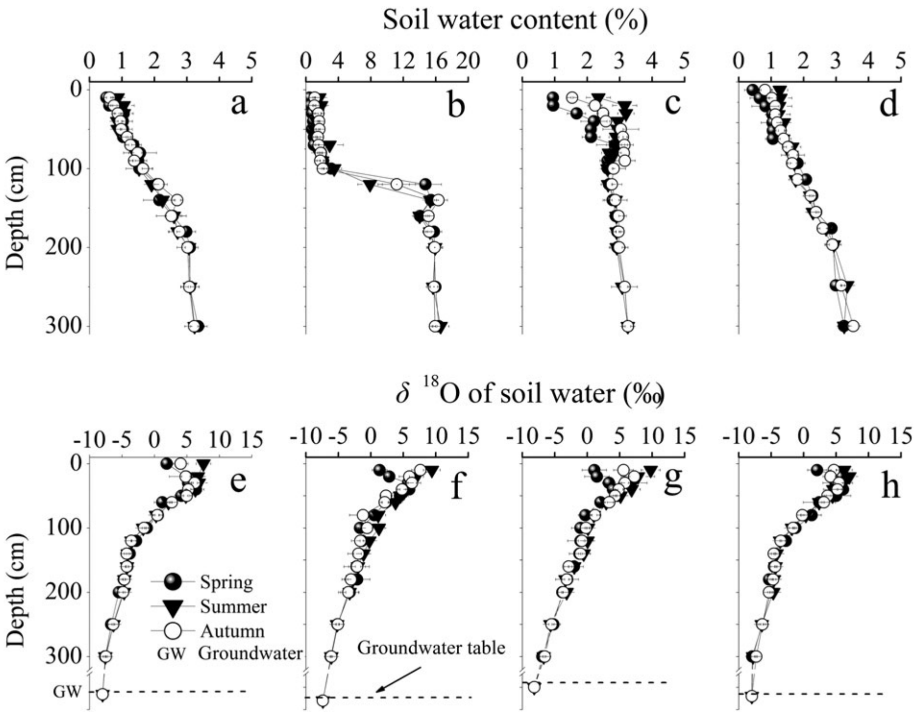

FIGURE 3 Vertical distribution of soil water content (SWC) and δ^{18}O values of soil water and groundwater measured in 5- (a and e), 10- (b and f), 20- (c and g), and 40-year-old (d and h) planted *Haloxylon ammodendron* forest during the growing season. Error bars represent standard errors of mean δ^{18}O values or SWC

and seasons—but not among the four study sites (Table 2). In the upper 40 cm of the soil profile, the δ^{18}O values of soil water were lowest at 1.37–2.35‰ in spring, and progressively increasing to a maximum of about 5.26–6.79‰ in summer. The δ^{18}O values of soil water at 40–150 cm exhibited relatively mild fluctuations with seasons (p < .05), while those below 150 cm had no significant seasonal variation (p > .05; Table 2). The shallow soil layers were consistently more enriched with the heavier isotope than the lower soil horizons and groundwater (Figure 3e–f; Table 2). Deep soil was usually more depleted in δ^{18}O than shallow soils but more enriched than groundwater. Soils at this depth had similar seasonal patterns of δ^{18}O to those of groundwater at all sites (Table 2).

The δ^{18}O of *H. ammodendron* stem water exhibited high variability within seasons and across stands (Figure 4; Table 2). During the growing season, 5-year-old plants had the highest δ^{18}O values in stem water, ranging from −3.15‰ in spring to 2.92‰ in summer. Seasonal variability in the isotopic ratio was almost synchronous with that in precipitation (Figure 3; Table 2) and reflected precipitation-influenced water sources of 5-year-old plants. The δ^{18}O values of 10-year-old plants also exhibited significant seasonal variability (p < .001), but they were consistently higher in spring than in the other two seasons and were similar to those of rainwater. In particular, the δ^{18}O values decreased significantly between mid-June and mid-September until they resembled the values for deep soil water and groundwater (Figure 4; Table 2). The 20- and 40-year-old plants had the lowest δ^{18}O values that fluctuated mildly with seasons and were similar to the values for deep soil water and groundwater. The δ^{18}O values of plants at different sites showed significant differences (p < .01; Figure 4; Table 2); this indicated that plant water sources ranged from shallow soil water recharged by precipitation to deep soil water and groundwater across the different sites.

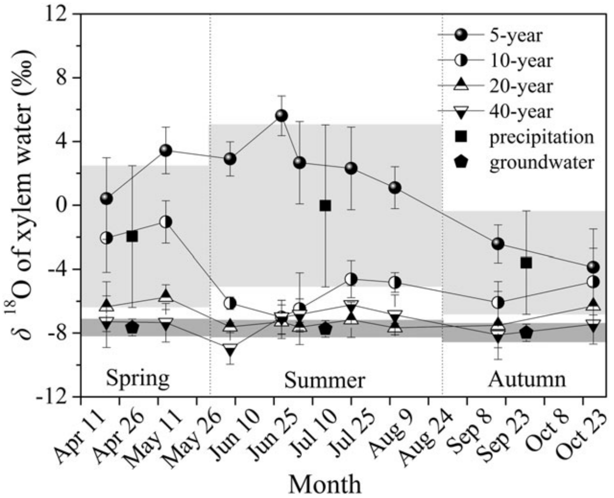

FIGURE 4 Oxygen isotope ratios (δ^{18}O) of precipitation, groundwater, and stem water for 5-, 10-, 20-, and 40-year-old planted *Haloxylon ammodendron* forest during the 2014 growing season. Error bars represent standard errors of mean δ^{18}O values for stem water, n = 3. Light-gray bars depict the average δ^{18}O values (±SD) for precipitation in each season (spring, summer, and autumn); dark-grey bars depict the average δ^{18}O values (±SD) for groundwater in each season

3.4 | Seasonal changes in plant water sources

The relative contribution of each water source (shallow, mid-, and deep soil layers and groundwater) to the water consumption of

H. ammodendron is shown in Figure 5 for each sampling month. The mixing models revealed that plants were able to uptake water from four water sources simultaneously, but in varying relative amounts, depending on the season. In spring (April and May), the contribution of shallow soil water to the water use of 5-year-old shrubs ranged from 61% to 75%, while that of mid- and deep soil water was 15.5–19.8% and 0–10.6%, respectively. However, contribution of shallow soil water to 5-year-old shrubs increased to 74–85% in summer (June to August), while that in autumn decreased rapidly. Water sources for 10-year-old shrubs also fluctuated with seasons. Contributions of shallow and mid-soil water to water use of 10-year-old shrubs were 16–24.4% and 24–33.4% in spring, respectively. During the summer, the contribution of shallow soil water decreased, while that of deep soil water and groundwater increased rapidly. Contributions of deep soil water and groundwater were in the range of 34.3–48% and 41.3–55.5%, respectively. However, water sources for the 20- and 40-year-old shrubs showed little seasonal fluctuation. The contributions of groundwater were in the range of 60.1–90.4% and 81–100%, respectively.

3.5 | SWC, δ^{18}O of soil water and plant water sources in response to precipitation pulses

SWC and δ^{18}O values of soil water exhibited clear changes with soil depth after the 24.8-mm and 8.0-mm rain events, with the largest change in water content occurring in the surface layer (Figure 6a–h). Both soil water and its δ^{18}O values within the 0–10-cm and 10–30-cm layers were significantly affected by rainfall and evaporation at all sites, and those within the 30–50-cm and 50–100-cm layers were only marginally or not affected.

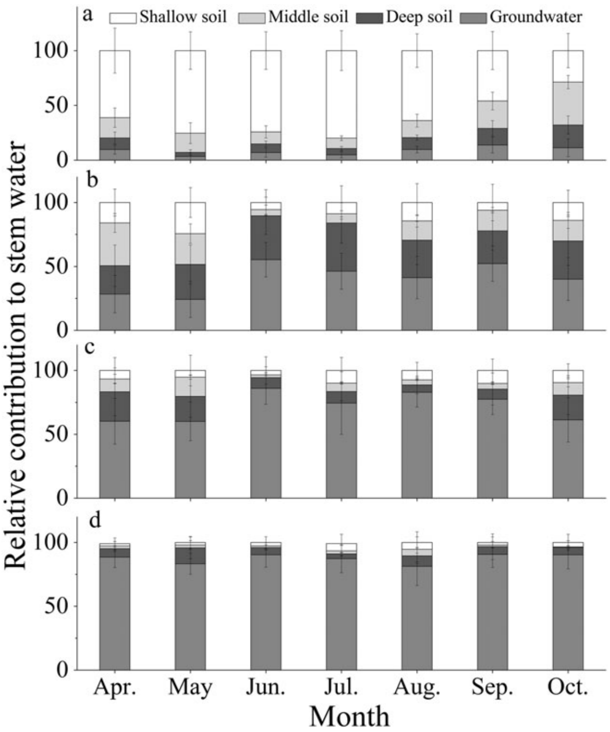

FIGURE 5 Seasonal changes in the relative mean contribution of soil water at different depths to 5-, 10-, 20-, and 40-year-old *Haloxylon ammodendron* plantations. Data obtained from the IsoSource mixing model: shallow soil (0–50 cm), mid-soil (50–150 cm), deep soil (150–300 cm), and groundwater (below 300 cm). Bars represent the possible ranges of potential water sources

In the top 10-cm and in the 10–20-cm layers, SWC reached a maximum of 1 day after precipitation and then rapidly decreased to the initial level within about 8 days at the 5- and 10-year-old sites. However, at the 20- and 40-year-old plantations, SWC decreased slowly and remained much higher than initial values 8 days after a rain event. The δ^{18}O values in both the 0–10-cm and 10–20-cm soil layers reached most closely to the value of precipitation 1 day after the event and then gradually returned to the initial values. However, values in the 20- and 40-year-old sites changed more slowly than at the two younger sites. This suggested that higher biomass at the two older sites had lower evaporation than did the younger shrub sites.

Based on the changes in δ^{18}O of plant stem water after a precipitation event, we found significant fluctuations in the contribution of precipitation to stem water within 8 days after rainfall. The δ^{18}O values in shrub stem water shifted towards the δ^{18}O value of the 24.8-mm event 1 day after and then gradually returned to the initial values. The 20- and 40-year-old shrubs exhibited small changes after the 8-mm rainfall; the δ^{18}O values of shrubs differed significantly from those of precipitation and were, on average, about halfway between precipitation and groundwater (Figure 7).

After precipitation, the relative proportion of shallow soil water used by shrubs increased noticeably at all sites (Figure 8). For 5-year-old shrubs, the relative proportion of shallow soil water used increased from 47% and 65.3% before to 75.5% and 84.3% on the first day, respectively, after the 24.8-mm and 8-mm rain and to a maximum of 86.3% and 85% on the second day and gradually decreased during the subsequent days. For 10-year-old shrubs, the contribution of shallow soil water increased from 8.3% and 9.6% before to 40.5% and 19.6% on the first day, respectively, after the 24.8-mm and 8-mm events and to a maximum of 42.5% and 20.9% on the second day. Meanwhile, the use of groundwater decreased from 67.8% and 65.4% to 29.3% and 41.4%, respectively, during the 24.8-mm and 8-mm rainfall events. Because the oxygen isotopic values of the rain and deep soil water were similar, IsoSource could not separate the two. For the 20- and 40-year-old shrubs, the contribution of shallow soil water also increased and differed for the two events. This indicated that the planted *H. ammodendron* responded to and used a certain amount of water supplied by precipitation.

4 | DISCUSSION

4.1 | The relationships between soil water and precipitation, and groundwater

Precipitation is the primary water source in the desert zone, and it determines plant-resource acquisition and survival in arid environments (Schwinning, Sala, Loik, & Ehleringer, 2004; Schwinning, Starr, & Ehleringer, 2005; Weltzin et al., 2003). Origins of water vapor, atmospheric flow paths of vapor trajectories, temperature, and precipitation amounts influence isotope ratios of precipitation (Yamanaka,

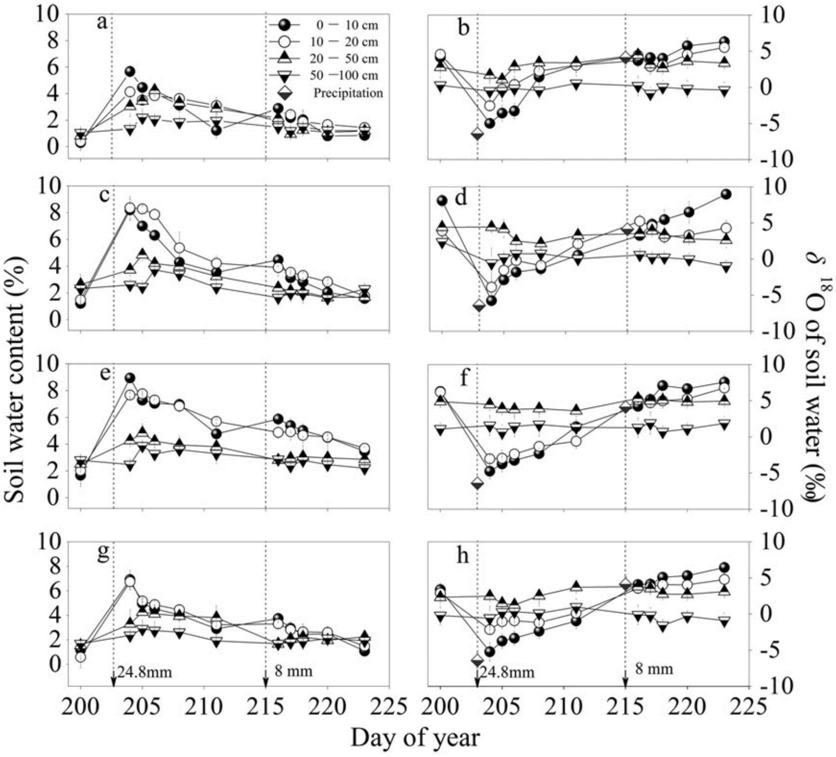

FIGURE 6 Temporal changes in soil water content (±SE; a, c, e, and g) and soil water δ^{18}O values (±SE; b, d, f, and h) before/after rain events (24.8 and 8 mm) in the soil profiles at 0–100 cm in the 5- (a and b), 10- (c and d), 20- (e and f), and 40-year-old (g and h) sites. Arrows indicate the rainfall day

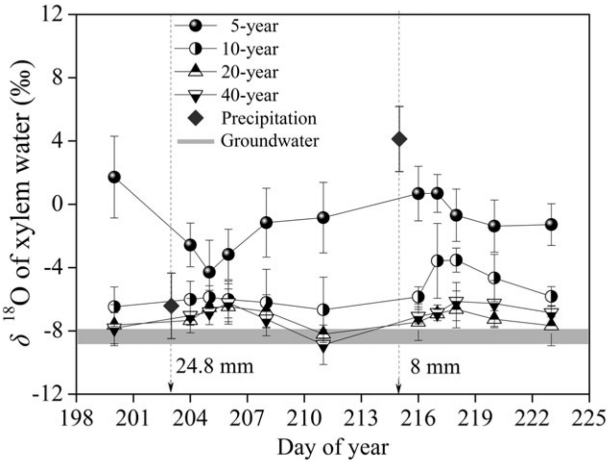

FIGURE 7 Temporal changes in δ^{18}O values (±SD) of plant stem water of the 5-, 10-, 20-, and 40-year-old planted *Haloxylon ammodendron* over an 8-day period after precipitation events (24.8-mm and 8-mm rainfall, respectively). The gray bar (a) depicts the average range of δ^{18}O values for groundwater after rainfall events

Tsujimura, Oyunbaatar, & Davaa, 2007; Liu, Song, Yuan, Sun, & Yang, 2014; Dai et al., 2014) and change those of soil water recharged by precipitation. At our sites, over 75% of the annual precipitation occurred in summer, and the δ^{18}O values of precipitation exhibited the rainfall-amount effect (Araguas-Araguas, Froehlich, & Rozanski, 1998). The mean δ^{18}O values of precipitation also showed significant seasonal fluctuations, with enriched values occurring in the hot summer months, and depleted values in spring and autumn. Precipitation patterns play a crucial role in plant water-use strategies in desert environments (Schwinning & Ehleringer, 2001), and the variation in precipitation is one of the main determinants of the growth and development of *H. ammodendron* plantations (Ma et al., 2007; Zhu & Jia, 2011).

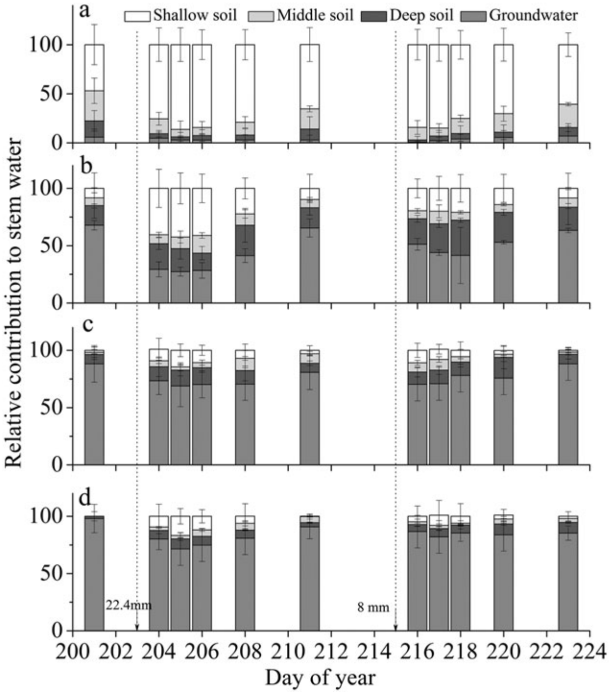

FIGURE 8 Variability in water sources for 5- (a), 10- (b), 20- (c), and 40-year-old (d) planted *Haloxylon ammodendron* before/after precipitation. Arrows indicate the day of a rain event. Bars represent the possible ranges of potential water sources

Soil water is the immediate source of water for plants. Although it is derived from meteoric water, many hydrological processes may cause this water to differ isotopically from the most recent precipitation (Tang & Feng, 2001). Temporal variations in SWC and δ^{18}O of soil water following rainfall events were determined by rainfall intensity, δ^{18}O signature of rainfall, antecedent soil water, and plant phenology

(Hsieh, Chadwick, Kelly, & Savin, 1998; Tang & Feng, 2001; Lee, Kim, Lee, Kim, & Lee, 2007; Xu et al., 2012). Soil water is generally a mixture of water from different precipitation events sometimes from different seasons. Heavy rainfall events (e.g., 24.8 mm) notably increased SWC, significantly influenced the oxygen isotope composition of soil water, and contributed to water $\delta^{18}O$ in deeper soil layers (Figure 6). Water in the topsoil had the lowest $\delta^{18}O$ values for all study sites in spring due to recharge by rain with relatively depleted isotope composition, and to low temperatures, which decreased evaporation and enrichment in the heavy oxygen isotope. However, $\delta^{18}O$ values of shallow soil water increased significantly in summer and early autumn due to strong evaporation and reached >5‰ (Figure 3e–h; Table 2).

Variations in $\delta^{18}O$ values of groundwater were smaller than those in precipitation and soil water (Figure 3 and Table 2). Soil water represents a mixture of many precipitation events and may have a relatively long average residence time, linking rainfall and groundwater; fluctuations in isotope compositions in soil water are indicative of the processes of precipitation infiltration, evaporation of soil water, and recharge of groundwater (Tang & Feng, 2001; Song et al., 2011). In contrast, $\delta^{18}O$ of deep soil water was similar to that of groundwater, suggesting that capillary rise from the water table controls soil water isotope chemistry in deep soil horizons. Another explanation for the more depleted soil values at depth is that only large rain events with depleted signatures contribute enough water to penetrate to any significant depth. Groundwater was isotopically depleted compared with the summer precipitation in Linze. Thus, the local precipitation may not be the dominant mechanism for groundwater recharge. Ehleringer and Dawson (1992) reported that the isotopic composition of groundwater was a weighted average of long-term precipitation input. The similarity in isotopic compositions of groundwater at our site and river water indicated that the mountain river was a major contributor to recharge in the southern basin. The calculated recharge altitudes indicated that recharge water came from the Qilian Mountains (Chen, Nie, Zhang, Wan, & Shen, 2006; Zhao, Liu, & Zhang, 2010; Liu et al., 2010).

4.2 | Variability in water sources of *H. ammodendron* plantations

The study shrubs experienced the highest amount of rainfall in the summer, and that was coupled with the highest temperatures in 2014 (Figure 2). The differentiation in water utilization by the four different-aged plantations, as determined by $\delta^{18}O$ during this period, suggested that adaptive variation in water uptake patterns existed among populations of *H. ammodendron*. In fact, most of the variability in water isotopes exhibited by the study plants could be attributed to the differences in root distribution and in soil areas from which water was absorbed; these differences define the depth to or volume from which plants can potentially extract water (Ehleringer, Phillips, Schuster, & Sandquist, 1991). *H. ammodendron* in the 5-year-old plantation used precipitation-derived upper soil water for survival and thus responded to rain pulses in terms of oxygen isotope of stem water. However, the species develops not only the shallow, resource-acquiring lateral roots but also deep-penetrating tap (sinker) roots with age (Table 2), a common trait in desert ecosystems. Shrubs in the 20- and 40-year-old plantations used mostly groundwater, which provided a relatively stable water source to address the extreme drought of the desert environment. Indeed, the survival of some species in desert ecosystems has been shown to fully depend on the ability of the plants to absorb water with tap roots from permanent water tables (Canadell et al., 1996, Pate, Jeschke, & Aylward, 1995).

For *H. ammodendron* plantations, the relationships between plant age and water sources showed that each age class drew water from different soil depths, older shrubs with deep roots drawing on a more $\delta^{18}O$-depleted, deeper water source than younger, more shallowly rooted shrubs (Figure 5). Water consumption increased with rooting depth and shrub size (Chang, Zhao, & Zhang, 2007; Zhu & Jia, 2011); thus, the plantation's need for a permanent water source, such as deep soil water and groundwater, to meet the transpiration demand, increased with plant size. Root systems also enlarged with plant size, to penetrate to deeper soil profile and provide access to groundwater table (Ehleringer, 1993; Dawson & Pate, 1996). Moreover, the availability of water to individual plants in such systems depends in part on the depth, lateral spread, and degree of overlap of plant root systems (Casper & Jackson, 1997). The initial density of *H. ammodendron* plantations in this study was too high (there were 2,825 individual/ha in the 5-year-old plantation) to maintain sustainable growth and development due to limited water sources. At such stand density, competition for water between shrubs would increase over time, potentially resulting in fewer surviving shrubs than in a lower density stand. We found that the roots in the 20- and 40-year-old stands were at groundwater depths and over 60% of water in those shrubs originated from groundwater. Shrubs in the 5-year-old plantation mainly use precipitation-derived shallow and mid-soil water. However, shrubs in the 10-year-old plantation derived the majority of their water from deeper sources, while after precipitation, they derived most of it from shallow sources (Figure 7).

The sources of water utilized by *H. ammodendron* were different in the four plantations and changed from shallow soil water, determined by precipitation, to groundwater, that has been recognized as a stable and reliable water source. Although the proportion of rainfall occurring during the summer was >80% in our study area, the shallow soil water only maintained shallower and short-lived soil moisture resources after precipitation events, because of high evaporative demand (Figure 6). This suggested that shallow soil water represented a limited water source for the planted shrubs. With an increase in shrub size and rooting depth, shrubs exploited deeper water sources to survive and to achieve sustainable growth. As soil water became less abundant, *H. ammodendron* appeared to acquire proportionally more water from deeper in the soil profile via tap roots regardless of plant size. However, a declining groundwater table would likely increase water stress in the plantation. Wang and Zhao (2015) found that the groundwater depths in the desert-oasis ecotone increased dramatically in the last years by 0.10–0.15 m per year. A deeper water table would likely mean that shrubs would need more time to develop sufficient roots to reach it. This would cause a period of heightened vulnerability in the shrub life history.

5 | CONCLUSIONS

Our results indicated that an evident self-thinning process occurred with age in *H. ammodendron* plantations. It may be due to insufficient water supply to maintain the physiological activity of a growing plantation. Variation in precipitation affects water use pattern of the plantation in desert area. The 5- and 10-year-old shrubs used mainly precipitation, but the 20- and 40-year-old shrubs used less precipitation. Soil water recharged by precipitation was consumed mainly by *H. ammodendron* with predominately shallow roots. The sustainable development of these plantations must rely on groundwater. If the density of young *H. ammodendron* plantations could be decreased to slow down soil water consumption, sustainability of these plantations would increase.

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