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Water Uptake from Different Soil Depths for Desert Plants in Saline Lands of Dunhuang, NW China

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Salinization is a major threat to the sustainability of land and water resources, especially in arid and semiarid regions. Understanding the water uptake from different soil depths for desert plants is useful for exploring salinity-tolerance mechanism in desert plants in extremely-arid and salinity-affected area. To understand water uptake from different soil depths for desert plants in Dunhuang, NW China, we used oxygen isotope composition in plant xylem water and soil water to determine the water sources in three different saline sites differing in their degree of soil electrical conductance (site 2 < site 1 < site 3). The co-existing desert plants in each saline site extracted different depth of soil water respectively: *K. foliatum* mainly used shallow soil water (0–20 cm); *H. caspica* and *N. tangutorum* mainly used deep soil water (40–200 cm); *A. sparsifolia* used water from the 120–200 cm soil layers, while *T. ramosissima* and *E. angustifolia* mainly extracted deeper soil water (>200 cm). Compared to that in saline site 2, *Tamarix ramosissima* and *Alhagi sparsifolia* can switch their water sources to deeper soil water when enduring more salt stress. Also, a significant and positive correlation between soil EC and soil water δ^{18}O values was observed, indicating the evaporation would cause increase in salt concentration and isotopic enrichment in the upper soil profile. Overall, our results suggest that plants may explore deeper soil water to adapt to salt stress under severe salinity. This work may contribute to selecting salt-tolerant plants species which is vital to saline soil rehabilitation and utilization.

Keywords: stable oxygen isotope, desert plants, saline land, soil water utilization, Dunhuang

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INTRODUCTION

Saline soil, as an important soil resource, amounts to more than 800 million hectares, which comprises over 6% of the world's total land area (Munns and Tester, 2008). Presently, the total area of saline soil resources is about 1.0×10^8 hm^2 in China (Wang, 1993), and the saline lands account for 7.74% of the total land area in Dunhuang, NW China (Sang, 2006). It is clear that abundant ecological, economic and social benefits could be attained if these saline lands are remedied and developed sufficiently. In recent decades, climate changes have profoundly affected natural and human systems (Field and Barros, 2014). Thereinto, climatic warming has intensified soil moisture evaporation and drives the soil salt to move upward, which exacerbate soil salinization (Xiao et al., 2010). There has been a temporal increase in magnitude and intensity of salt-affected soils (Qadir et al., 2000) because of irrational human practices, such as excessive fertilizer use, irrational irrigation and deforestation. To date, soil salinization has been a worldwide problem and has attached much significance by governments and scientists (Wang, 2009). Salt accumulation in the soil generally change the soil texture and decrease the soil porosity, and consequently reduce the soil aeration and water conductance, causing differences in water use among plant species.

Soil water is a key restricting factor influencing the survival of desert plants of saline lands in arid regions. Soil depths of water uptake for plants could be determined by comparing the stable isotope hydrogen (D) and oxygen compositions (^{18}O) of soil water and plant xylem water, as the isotope composition of xylem water remains unchanged during water transport from roots to stems (Ehrlinger and Dawson, 1992; Dawson et al., 2002; Šantrůček et al., 2007). In desert ecosystems, coexisting plant species may absorb water from different sources, such as soil water at different depths, groundwater, rain, etc. The differences in root distribution have been considered to be the mechanisms for the coexistence of diversified plant species in desert ecosystems (Zhou et al., 2013; Tiemuerbieke et al., 2018). For example, most shallow-rooted grasses take advantage of water in the shallow soil layers, while shrubs utilize a deeper soil water (Soriano and Sala, 1984). Moreover, some plant species shift soil depth of water uptake under altered environmental conditions. Chen et al. (2017) reported that the main water sources for *Caragana microphylla* shifted from topsoil to deeper soil in the dry season. Zhu et al. (2014) found that the 3-year-old *Tamarix ramosissima Ledeb.* and *Lycium barbarum L.* accessed more water in the deep profile after applying irrigation. Zhai et al. (2016) made a prediction of plant vulnerability to salinity increase in a coastal ecosystem, and found that hammock trees that took up water with higher salinities, had higher δ^{18}O values of plant stem water. In addition, high soil salinity may make plant water uptake increasingly difficult owing to the changes of soil texture (Mahajan and Tuteja, 2005; Yang et al., 2007). Therefore, plants may switch to more stable water sources under some environmental stress. Thus, plants may access more deeper soil water when suffering from increasingly salinity stress in desert systems.

To date, little is known about the water sources of desert plant species in saline lands in extremely-arid regions. Little rainfall, strong evaporation and rapid groundwater table lowering (Bai, 2009) undoubtedly affects the water utilization of desert plant in saline lands in Dunhuang. Thus, the objectives of the present study are 1) to determine the soil depth of water uptake for coexsiting desert plant species in each saline site; 2) to compare the soil depth of water uptake for common plants (*Tamarix ramosissima* and *Alhagi sparsifolia*) across different saline sites. This study may provide insight into plant-soil water relation of desert plants of saline lands in extremely arid regions and will help us to fully understand the responses of species to ongoing climate changes.

DATA AND METHODS

Study Area

Our study sites were located in the westernmost point of Hexi Corridor of Gansu province, within Dunhuang City (39°40′–41°35′N, 92°13′–95°30′E; average altitude of 1,138 m), northwestern China. The study area is characterized by a typical warm temperate continental arid climate with low rainfall and intense evaporation. The average annual precipitation (1938–2003) was 39.8 mm, with more than 67% occurring from June to August, while the mean annual potential evapotranspiration (PET) was 2,486 mm (Zhang, 2008). The mean annual temperature was 9.8°C, and the minimum and maximum mean monthly temperatures are −15.6°C and 32.8°C, respectively (Zhang, 2008). In the sampling year of 2011, the annual precipitation was 38.3 mm, with 27.3 mm occurring in June-August (Data from the National Meteorological Information Centre, China Meteorological Administration). The predominant soils in study area are salinized silts and sands containing clay interlayers. Vegetation are representative of those occurring throughout Dunhuang area, and are dominated by *T. ramosissima* and *A. sparsifolia*. Water table in this study area is about 60 m below the surface (Cui, 2014). Three saline sites differing in their degree of soil electrical conductance (EC, site 2 < site 1 < site 3) were selected in this study. Detailed site information including locations, dominant species and their life forms, is shown in **Table 1**.

TABLE 1 | Geographic characteristics of study sites, plant species and life form.

Sites	Locations	Altitude(m)	Dominant species	Life form
Saline site 1	40.20°N, 94.72°E	1,110	*Tamarix ramosissima*	Shrub
			Alhagi sparsifolia	Shrub
			Kalidium foliatum	Shrub
			Elaeagnus angustifolia	Arbor
Saline *site* 2	40.21°N, 94.72°E	1,109	*Tamarix ramosissima*	Shrub
			Alhagi sparsifolia	Shrub
Saline *site* 3	40.24°N, 94.63°E	1,105	*Tamarix ramosissima*	Shrub
			Alhagi sparsifolia	Shrub
			Halostachys. caspica	Shrub
			Nitraria. tangutorum	Shrub

Sample Collection

Plant and soil sampling took place in three sites in July 2011. At each site, three plant communities (ca. 5 × 5 m^2) were randomly selected, where all sampling and measurements were conducted. 2-4 dominant plant species present in each community were studied for water uptake. Two common species, *T. ramosissima* and *A. sparsifolia*, were sampled in the three saline sites (**Table 1**).

Plant xylem sample were collected from the non-photosynthetic tissues during the morning period, and were immediately placed in 8 ml glass vials (National Scientific Company, United States) after removing the bark and phloem. The glass vials were sealed by parafilm (Alcan Packaging, WI, United States) and stored in a cool ice chest for delivery to the laboratory. In the laboratory, xylem samples were stored at −20°C before water extraction.

Concurrent with plant xylem sampling, three soil pits per site near studied plants were augured using a hand auger. Soil samples were collected at depths of 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, 80–100 cm, 100–120 cm, 120–160 cm and 160–200 cm. Then each soil sample was separated into three parts for measurements for soil water content (SWC), soil EC, pH, ion content and stable isotope composition, respectively. Fresh soil for determination of SWC were sealed in soil tin. The soil samples for measurements of soil EC, pH, ion content were stored in plastic bags, then sieved and air-dried later. The soil samples for stable isotope analysis were immediately put into 10-ml screw-cap glass vials, then sealed with Parafilm and placed in a portable cooler for transporting back to the laboratory. To prevent evaporative isotopic fractionation, the soil samples for stable isotope analysis were stored in a refrigerator (at −20°C) in the laboratory until water extraction.

Isotopic Analyses

Water was extracted from plant stems and soil samples by cryogenic vacuum distillation (Dawson et al., 1993; Ehleringer et al., 2000; Horton et al., 2003). Water samples were measured for isotopic ratios of hydrogen (δD) and oxygen ($\delta^{18}O$) in an isotope ratio mass spectrometer (DELTA V Advantage, Thermo Fisher Scientific, Inc., Waltham, MA, United States) interfaced with an elemental analyzer (Flash EA1112 HT, Thermo Fisher Scientific, Inc., Waltham, MA, United States). The stable hydrogen and oxygen isotope were expressed as delta (δ) values per mil (%) relative to Vienna standard mean ocean water (V-SMOW) (Einbond et al., 1996), as shown in the following equation:

$$\delta = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1\right) \times 1,000,$$

where R_{sample} and R_{standard} are the ratio of the heavy to the light isotope in a sample and the standard, respectively. The analytical error for δD and $\delta^{18}O$ were ±1% and ±0.2%, respectively.

Based on the similarities in $\delta^{18}O$ values for the soil water in each layer, and $\delta^{18}O$ values of xylem water, we divided the soil profile into five major sections (0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm and 80–200 cm) in the three saline lands. The isotopic composition for each depth was according to the average value of samples within each interval. The isotope values of each interval and the xylem water were analyzed by the IsoSource software (the multi-source mass balance approach) to evaluate the contribution of each soil depth to xylem water. The IsoSource mixing model (http://www.epa.gov/wed/pages/models/stableIsotopes/isosource/isosource.htm) (Phillips and Gregg, 2003) used stable isotope values to determine the relative contributions of soil water to xylem water. The source increment was defined as 1% and mass balance tolerance was defined as 0.1%.

Measurements of SWC, Soil EC, pH and Ion Content

SWC was determined by a conventional loss-on-drying method and expressed in percentage of gravimetric water content [(g water/g dry soil) × 100%] (Wang and Chen, 2010). Electrical conductivity of 1:5 water extracts, made by adding 25 g of deionized water to 5 g of each sample (Dehaan and Taylor, 2002), were used to reflect soil EC, using a DDS-307 Conductivity Meter (LeiCi Co. Ltd., Shanghai, China). Soil pH was determined by a pH-3D pH meter (ZhiGuang Co. Ltd., Shanghai, China). Ca^{2+} and Mg^{2+} were determined by EDTA complexing titration, and Na^{+} and K^{+} contents were measured with flame spectrometry using a flame photometer (FP640; Shanghai Precision Science Instrument, China). Cl- was determined with $AgNO_3$ titration, HCO_3^{-} and CO_3^{2-} were determined using titration with hydrochloric acid, and SO_4^{2+} was indirectly determined through titration with EDTA (Qadir et al. 2007).

Data Analysis

All statistical analyses were performed with SPSS software (version 17.0, SPSS Inc., Chicago, IL, United States). Multiple comparisons of isotope values for the soil water from all individual layers used a one-way analysis of variance (ANOVA) with Fisher's least significant difference method. Significance was determined at the 95% confidence level ($\alpha = 0.05$). Pearson's correlation was calculated to determine the relationship between $\delta^{18}O$ values, SWC, soil EC, and pH in soil profile. Charting was processed using the software Origin 9.0 (OriginLab Corp., Northampton, MA, United States).

RESULTS

SWC, EC and pH

Soil water content profiles varied significantly in the three saline sites (**Figure 1**). Overall, SWC was higher in the saline site three than that in the saline site one and saline site 2 ($p < 0.05$). In the saline site 1, SWC in 0–80 cm soil profile was significantly higher than that in 80–200 soil profile ($p < 0.05$): SWC varied little in the 0–80 cm soil layers, and showed a little decrease in 80–100 cm soil layers, and then increased in 100–200 cm soil layers. Significant soil profile differences were detected in the saline site 2 ($p < 0.01$): a peak of 11.3% in SWC occurred in 20–40 cm soil layer, and SWC showed little variation in 60–120 cm soil layers, and then increased steadily with depth to 11.3% again in 160–200 cm soil layers. In the saline site 3, SWC showed a decreasing trend from surface soil to deeper soil depths.

Significant site differences were detected in soil EC, especially in 20–100 cm soil layers, with lower soil EC values in the saline site two than that in the saline site one and saline site 3 ($p < 0.05$). Significant variations of soil EC among soil depths were observed in each saline site ($p < 0.05$). Soil EC decreased with soil depth and the highest soil EC was recorded in 0–20 cm soil layer in each saline site (**Figure 1**). Based on the equivalent-ratio of Cl^{-}/SO_4^{2-}, saline soil can be divided into four types of saline soil, which are chlorinate (≥4) sulfate-chlorinate (4–1), chlorinate-sulfate (1–0.5) and sulfate (<0.5) solonchak respectively (Wen, 2014). In this research, the soil salinization type of the three saline sites were the same type of saline soil which was sulfate solonchak (**Figure 2**).

No significant difference in soil pH value was observed across the three saline sites ($p > 0.05$), except that the soil pH in

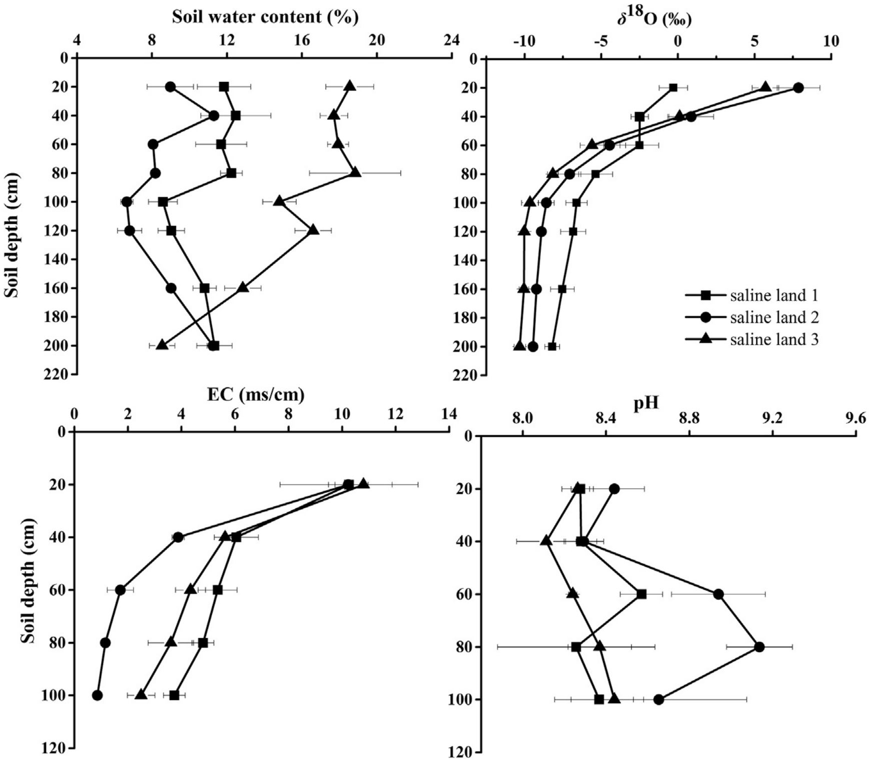

FIGURE 1 | Variation in soil water content, soil water δ^{18}O values, soil electrical conductivity (EC) and pH along soil profiles in the three saline sites. Data are presented as mean ± 1 SE.

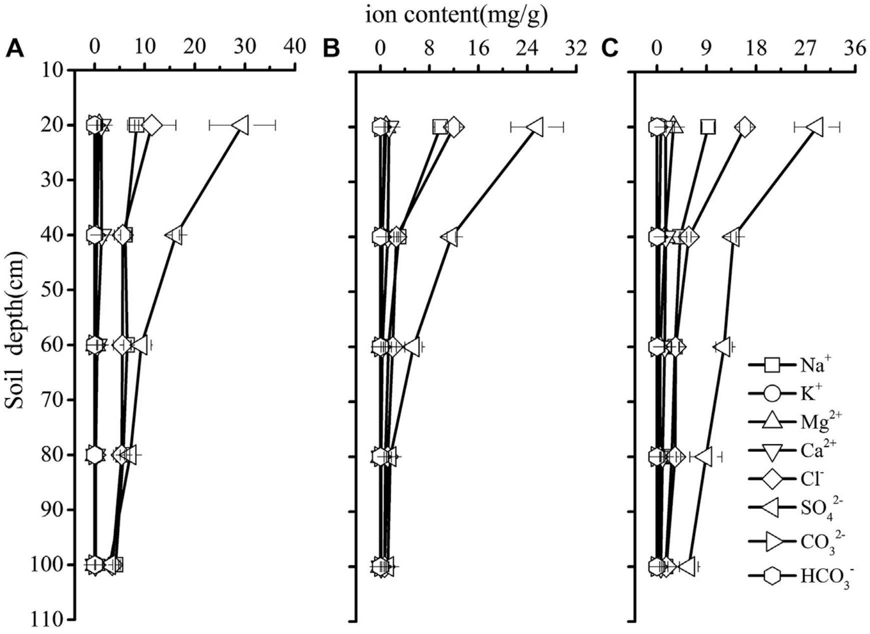

FIGURE 2 | Soil salinity distribution in the saline site 1 **(A)**, saline site 2 **(B)** and saline site 3 **(C)**. Data are presented as mean ± 1 SE.

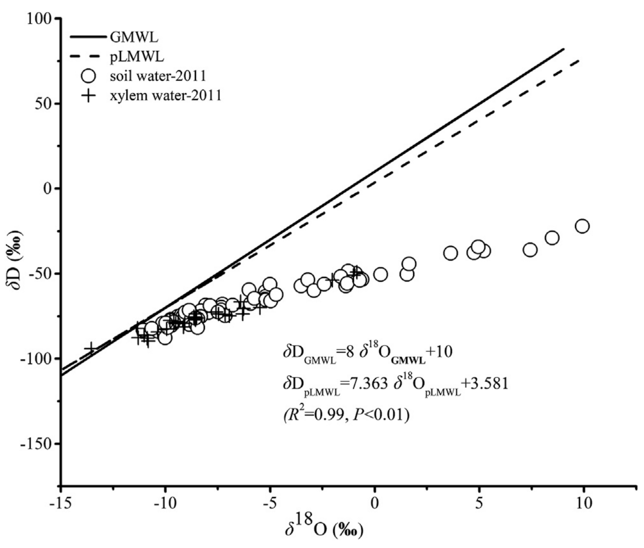

FIGURE 3 | Relationship between δD and δ^{18}O in soil water and xylem water. The Global Meteoric Water Line (GMWL) and the predicted Local Meteoric Water Line (pLMWL) were also presented.

40–60 cm soil layer was higher significantly in the saline site two than that in the saline site 3 ($p < 0.05$). In each saline site, no apparent variation was found in soil pH value among the soil layers (saline site 1: $p = 0.80$; saline site 2: $p = 0.15$; saline site 3: $p = 0.31$).

δ^{18}O Values for Soil Water and Xylem Water

There were linear relationships between δD and δ^{18}O for soil water and xylem water in the study sites (**Figure 3**). δD and δ^{18}O for Dunhuang were estimated by the Online Isotopes in Precipitation Calculator (OIPC; http://www.waterisotopes.org/) and the predicted Local Meteoric Water Line (pLMWL) was created. All the samples of soil water plotted below the global meteoric water line (GMWL) and pLMWL, indicating the strong evaporation enrichment and the extremely dry conditions. It can be noted that lower δD and δ^{18}O values were found for xylem water, indicating that the studied plants took up water predominantly from soil water with lower δD and δ^{18}O values.

The δ^{18}O values of soil water across the three saline sites differed significantly ($p < 0.05$) in some soil layers (0–20 cm and 80–200 cm) (**Figure 1**). The δ^{18}O values of soil water in each saline site showed a clear decreasing trend along the soil profile. The δ^{18}O values of soil water decreased rapidly 6.31, 16.45 and 15.36% from 0 to 100 cm in the saline land 1, saline land two and saline land three, respectively. In contrast, from 100 to 200 cm, no trend in δ^{18}O values of soil water was observed. The soil water in 0–20 cm soil layer had the highest mean δ^{18}O value (−0.30, 7.87, and 5.71% for saline site 1, saline site 2 and saline site 3, respectively). The δ^{18}O values of soil water varied significantly with soil depth, with variation in the upper layers (0–100 cm) greater than in the deep soil layers (>100 cm).

Table 2 summarizes the xylem water δ^{18}O values collected in the three saline sites. Variations in the δ^{18}O values of xylem water among plant species were observed in each saline site. In the saline site 1, *K. foliatum* had significantly higher δ^{18}O values than *A. sparsifolia*, *E. angustifolia* and *T. ramosissima* ($p < 0.01$). In the saline site 2, no apparent variation in the xylem water δ^{18}O values was observed between *T. ramosissima* and *A. sparsifolia*. In the saline site 3, *T. ramosissima* had significantly lower xylem water δ^{18}O values than *A. sparsifolia*, *H. capsica* and *N. tangutorum* ($p <$ 0.01). For the same plant species, no significant difference in mean xylem water δ^{18}O values was observed across the different saline sites (*T. ramosissima*: $p = 0.07$; *A. sparsifolia*: $p = 0.66$), whereas multiple comparison tests found that the xylem water of *T. ramosissima* in the saline site two was significantly higher in ^{18}O by −1.41% than that in the saline site 3.

Water Uptake from Different Soil Depths for Desert Plants in the Three Saline Lands

We caculated the contributions of water used by plant species from five ranges of soil depths (0–40 cm, 20–40 cm, 40–60 cm, 60–80 cm and 80–200 cm) by the IsoSource model. The IsoSource outputs showed that, in the saline site 1, *K. foliatum* used average 68.3% soil water from 0 to 20 cm soil layers, and there was no IsoSource solution for *A. sparsifolia*, *E. angustifolia* and *T. ramosissima*, because the mean xylem water δ^{18}O values were beyond the confine of those of potential water sources (**Table 3**). Then we inferred the soil depth of water extraction by *A. sparsifolia*, *E. angustifolia* and *T. ramosissima* by the overlapping δ^{18}O values for xylem water and soil water (**Figure 4**). In the saline site 1, *A. sparsifolia* extracted water from the 120–200 cm soil layers, while the δ^{18}O values of *T. ramosissima* and *E. angustifolia* were more negative than those of 0–200 cm soil water, which indicated that *T. ramosissima* and *E. angustifolia* mainly extracted deeper soil water (>200 cm).

The IsoSource outputs showed that *A. sparsifolia* primarily used soil water from 80 to 200 cm (average 80.2%) and there was no IsoSource solution for *T. ramosissima* in the saline site 2 (**Table 3**). Overlapping δ^{18}O values for xylem water of *T. ramosissima* and soil water were detected in the saline site 2. We inferred *T. ramosissima* utilized water from 120-200 cm soil layers (**Figure 4**).

TABLE 2 | The δ^{18}O values of plant xylem water in the three saline *sites*.

Sites	Species	xylem water δ^{18}O ± SE (%)
Saline site 1	*T. ramosissima*	-9.97 ± 0.49^{a}
	A. sparsifolia	-9.75 ± 1.94^{a}
	E. angustifolia	-10.17 ± 0.59^{a}
	K. foliatum	-1.30 ± 0.37^{b}
Saline site 2	*T. ramosissima*	-9.65 ± 0.38^{a}
	A. sparsifolia	-8.21 ± 0.38^{a}
Saline site 3	*T. ramosissima*	-11.06 ± 0.12^{a}
	A. sparsifolia	-8.61 ± 0.58^{b}
	H. caspica	-6.33 ± 0.04^{c}
	N. tangutorum	-6.98 ± 0.87^{bc}

Data are presented as mean ± 1 SE.

[a,b,c] *Statistically significant differences among different species in each saline site ($p < 0.05$; LSD).*

TABLE 3 | Properties of feasible water sources (%) for desert plants in the three saline lands [mean (min-max)].

Sites	Species	Water sources				
		Soil depths (cm)				
		0–20	**20–40**	**40–60**	**60–80**	**80–200**
Saline land 1	*T. ramosissima*	—	—	—	—	—
	A. sparsifolia	—	—	—	—	—
	E. angustifolia	—	—	—	—	—
	K. foliatum	68.3 (55–85)	11.8 (0–43)	11.7 (0–45)	4.8 (0–19)	3.4 (0–14)
Saline land 2	*T. ramosissima*	—	—	—	—	—
	A. sparsifolia	1 (0–4)	2 (0–8)	4.9 (0–18)	11.9 (0–42)	80.2 (58–94)
Saline land 3	*T. ramosissima*	—	—	—	—	—
	A. sparsifolia	2 (0–8)	3.3 (0–13)	8.3 (0–32)	20.6 (0–76)	65.7 (24–90)
	H. caspica	6.8 (0–23)	10.6 (0–36)	22.6 (0–83)	29.6 (0–86)	30.5 (0–75)
	N. tangutorum	5.1 (0–19)	8.1 (0–30)	18.6 (0–68)	31.7 (0–91)	36.5 (0–80)

Note: Oxygen isotope values were used for the calculations. Average source proportions calculated by the model are shown, as well as range of minimum and maximum source proportions. "–"indicate no IsoSource solution.

The IsoSource outputs showed that average 65.7% of water source of *A. sparsifolia* came from 80 to 200 cm soil layers, *H. caspica* and *N. tangutorum* used little water from depths of 0–20 cm (average 6.8% and 5.1%, respectively), instead derived most of its water from deeper soil layers (40–200 cm) in the saline site 3 (**Table 3**). There was no IsoSource solution for *T. ramosissima*, and the δ^{18}O values of *T. ramosissima* were more negative than those of 0–200 cm soil water. So, we inferred that *T. ramosissima* mainly extracted soil water at depths of >200 cm in the saline site 3 (**Figure 4**).

Relationship Between SWC, Soil EC and Soil Water δ^{18}O

The relationship between SWC and soil water δ^{18}O values in 0–200 cm soil profile was analyzed for each saline site, and the result showed that SWC correlated positively with soil water δ^{18}O values for 0–200 cm soil profile in the saline site 1 ($R = 0.42$, $p > 0.05$) and saline site 3 ($R = 0.49$, $p < 0.05$), while no obvious correlation was observed in the saline site 2 ($R = 0.20$, $p = 0.35$). Whereas, it was found that there was no significant correlation between SWC and soil water δ^{18}O values in 0–200 cm soil profiles of the whole study area either ($R = 0.18$, $p = 0.13$). The correlations among SWC, soil water δ^{18}O, soil EC, and soil pH values in the 0–100 cm soil profile were also analyzed for each saline site. For the 0–100 cm soil profile, soil EC correlated positively with soil water δ^{18}O values in each saline site, but no significant correlation was observed between SWC and soil water δ^{18}O values (**Table 4**).

DISCUSSION

Variations in Soil Water Isotopic Composition

In the three studied saline sites, a vertical isotopic gradient in soil water δ^{18}O profiles was observed (**Figure 4**), with ^{18}O-enrichment of surface soil water, indicating the occurrence of evaporation. The light isotope is easier to evaporate during evaporation, which makes the liquid water enrich in heavy isotopes, and evaporation mainly occurs in the soil surface layer (Li and Liu, 2008). Therefore, along the soil depths, the enrichment of heavy isotopes decreases (**Figure 4**). Zimmermann et al. (1967) reported the effect of soil water evaporation on hydrogen isotopes. They showed that evaporation at the surface of a saturated soil column leads to D-enrichment near the surface soil layer, which decreases exponentially with soil depths. The enrichment trend may occur as a result of several processes, including evaporation, change in isotopic composition of precipitation and mixing of new and old water. However, the average annual rainfall of Dunhuang is only 39.8 mm (Data from the National Meteorological Information Centre, China Meteorological Administration). Under such extremely arid climate conditions, the rain has evaporated before it infiltrates into the soil. Therefore, in this study, the impact of precipitation on soil water could be ignored. Similar soil water δ^{18}O-profiles were also found in the Heihe Basin (Zhao et al., 2008; Zhou et al., 2011; Zeng and Ma, 2013). Zhao et al. (2008) evaluated water sources of riparian plants in the extremely arid region along the lower reaches of the Heihe River basin by stable isotope technique. They found that soil water isotope concentrations decreased approximately exponentially with depth to a relatively constant concentration. Zhou et al. (2011) used D and ^{18}O to determine the water sources of sand dune plants in middle reaches of Heihe River, and showed δ D and δ^{18}O values of soil water decreased as a typical exponential function of depth, except that some details of the exponential curve were altered by the infiltration of individual rainfall events. Zeng and Ma (2013) also found that δ D and δ^{18}O values of soil water soil water decreased along soil depths in two different habitats (oasis-desert transitional zone and desert) in the Heihe River Basin.

In previous studies in arid regions, it was found that soil with less water content in the upper layers usually has more enriched δ^{18}O values, and soil with more water content in the deeper soil layers has more depleted δ^{18}O values (Wu et al., 2014; Liu et al., 2015; Zhou et al., 2015). However, no significant and negative correlations between SWC and soil water δ^{18}O values were

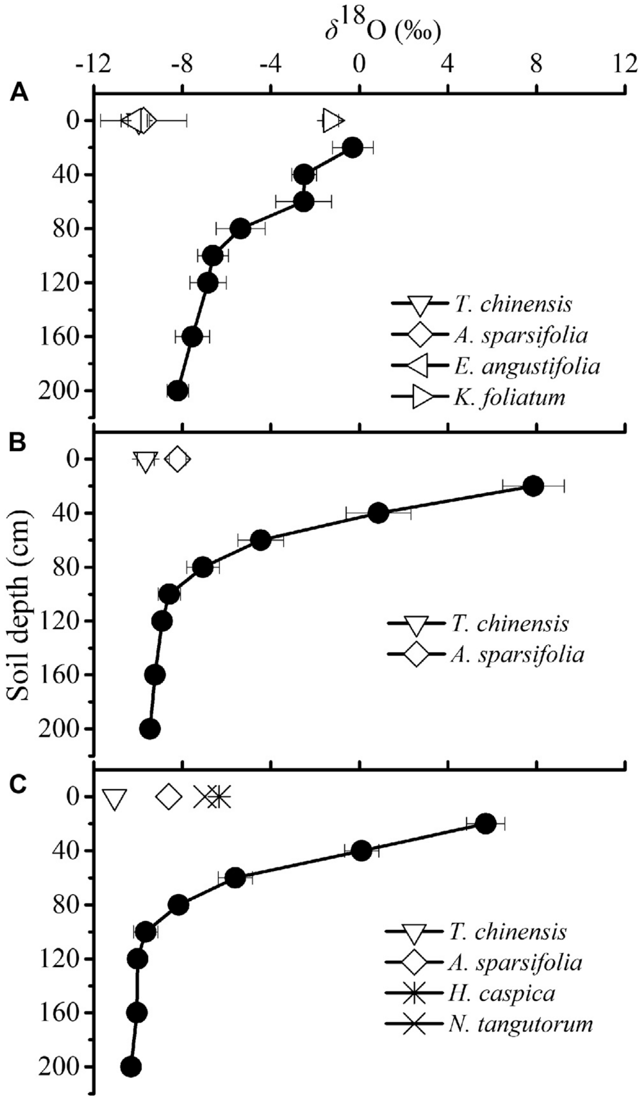

FIGURE 4 | Variation in the δ^{18}O value of soil water in the saline site 1 **(A)**, saline site 2 **(B)** and saline site 3 **(C)**. Xylem water δ^{18}O values of the dominant species are also presented in each saline site. Data are presented as mean ± 1 SE.

observed in each saline site. It is noted that significantly positive correlation or no obvious correlation were found between SWC and soil water δ^{18}O values in this study, which is incongruous with previous result that soil water content is negatively correlated with soil water δ^{18}O values (Zhu et al., 2014; Cui et al., 2017). Whereas, a significant and positive correlation between soil EC and soil water δ^{18}O values in 0–100 cm soil profile was observed in each saline site (**Table 4**), indicating that intense evaporation exerted significant enrichment effects on soil water δ^{18}O values in soil profiles and cause more soil salt assembled on soil surface. Zhu et al. (2014) investigated the water uptake for halophyte grown in Northern area of Ningxia plain (China) in contrasted water regimes, and found similar relations that significant and positive correlations between soil salt content and soil water δ^{18}O values. The positive correlation between salinity and δ^{18}O was also observed in many field studies on water table, such as Sternberg et al. (1991); Lin and Sternberg (1994), Ewe et al. (2007), which may result from mixing of freshwater with low δ^{18}O values and saline seawater with high δ^{18}O values. Zhai et al. (2016) found there was a curvilinear relationship between salinity and the δ^{18}O values in the vadose zone. However, it was considered that high salinity will significantly restrain the evaporation fractionation of soil water, and thus δ D and δ^{18}O values will be depleted (Li and Qiu. 2018; Din et al., 2020). In this study, heavy isotopes (^{18}O) were enriched in the liquid phase as water evaporated due to intense soil evaporation (Li and Qiu. 2018). Meanwhile, stronger soil evaporation could cause more salt accumulation and even surface assembled.

Variations in Soil Depth of Water Uptake for Different Desert Plants in Each Saline Site

Co-existing desert plant species in the same saline site exhibited obvious variations in depth of water uptake respectively. In the saline site 1, *K. foliatum* used average 68.3% soil water from 0 to 20 cm soil layers; *A. sparsifolia* extracted water from the 120–200 cm soil layers, while *T. ramosissima* and *E. angustifolia* mainly extracted deeper soil water (>200 cm). In the saline site 2, *A. sparsifolia* primarily used soil water from 80 to 200 cm (average 80.2%) and *T. ramosissima* utilized water from 120–200 cm soil layers. In the saline site 3, *A. sparsifolia* used average 65.7% soil water from 80 to 200 cm soil layers; *H. caspica* and *N. tangutorum* derived most of water from deeper soil layers (40–200 cm); *T. ramosissima* mainly extracted soil water at depths of >200 cm (**Table 3**). The xylem water δ^{18}O values varied among the studied co-occurring plant species in the studied sites, which indicated that interspecific differences in water absorption. The differences in xylem water δ^{18}O values is very small, but the water sources may vary among the co-occurring plant species (Min et al. 2019). The variations in soil depth of water uptake for co-occurring plant species would lead to niche segregation and complementary use of limited water resources, and facilitated plant species co-existence (Asbjornsen et al., 2008). In this study, *K. foliatum* depended mainly on shallow soil water, which is in accordance with its root distribution pattern (a relatively shallow root system with taproots penetrate to 20–30 cm deep and spindly adventitious roots) (Shi and Wang, 2003; Yang et al., 2013). *A. sparsifolia* utilized deep soil water in the three saline sites. Wang et al. (2017) got similar result that during the growing season, *A. sparsifolia* acquired soil water stored at 50–200 cm soil depth in the lower reaches of Tarim River. It has been reported that *A. sparsifolia*'s roots could penetrate up to 12–30 m deep (Shi, 2003). In this study *E. angustifolia* extracted soil wate**r** below the depth of 200 cm. *E. angustifolia* is a kind of deciduous tree, and it has been reported that their roots can extend into deeper soil layers (Shi and Qu, 2003). *H. caspica* and *N. tangutorum* mainly derived water from 40-200 cm soil depths in saline site 3. This is accordance with their root distribution that their absorbing roots mainly developed in 0–200 cm soil layers (Sun and Yu, 1992). In this study *T. ramosissima* attached soil water of middle

TABLE 4 | Relationship among soil water content (SWC), soil water oxygen composition, soil electrical conductivity (EC) and pH (0–100 cm).

	Saline land 1				Saline land 2				Saline land 3			
	SWC	**$\delta^{18}O$**	**EC**	**pH**	**SWC**	**$\delta^{18}O$**	**EC**	**pH**	**SWC**	**$\delta^{18}O$**	**EC**	**pH**
SWC	1.00				1.00				1.00			
$\delta^{18}O$	0.42	1.00			0.44	1.00			0.29	1.00		
EC	0.60*	0.60*	1.00		0.32	0.94**	1.00		0.48	0.91**	1.00	
pH	−0.31	−0.14	−0.22	1.00	−0.25	-0.53*	−0.43	1.00	−0.65**	−0.36	−0.42	1.00

Note: Asterisk represents the significance of coefficient, $^*p < 0.05$, $^{**}p < 0.01$.

or deep soil layers. There are many literatures on *T. ramosissima*' water sources by stable isotope technique, which got the result that *T. ramosissima* was a facultative phreatophyte and mainly relied on deep soil water and groundwater (Zhou et al., 2013; Wang et al., 2017). For example, Studies in the southeastern Junggar Basin have shown that *T. ramosissima* obtained 90% of its water from deep soil water and groundwater (Zhou et al., 2013). The vertical root distribution seemed determine the soil depth from which plant species can potentially access water (Ehleringer et al., 1991; Xu and Li 2006; Zhou et al., 2015; Zhang et al., 2017). However, some study in the Gurbantonggut desert found that *T. ramosissima* mainly relied on middle to deep soil water (Tiemuerbieke et al., 2018). This inconsistency suggests that plant water uptake was determined by root activity rather than root presence (Dawson and Ehleringer, 1991; Prechsl et al., 2015). Moreover, Imada et al. (2013) reported that *T. ramosissima's* fine root distribution was drastically changed by soil water and nutrient distribution. So, it is indicated that the distribution of active roots showed substantial ecological plasticity in response to soil water and nutrient. Overall, root is an important determinant of the availability of soil water and is closely related with plant–water relations (Nippert et al., 2010).

Variations in Soil Depth of Water Uptake for Common Desert Plants Across the Three Saline Sites

For the common species, despite no habitat effects on xylem water $\delta^{18}O$ values, the depth of water uptake for common species differed across the three saline sites. According to **Figure 4**; **Table 3**, we compared the soil depth from which common plant species may access across the three saline sites, and observed that *T. ramosissima* and *A. sparsifolia* attached more shallow soil water in the saline site 2 than in the saline site 1 and 3. The soil EC in the saline site 2 was the lowest among the three saline sites. This accordance with changes in soil EC suggests that *T. ramosissima* and *A. sparsifolia's* water use could be influenced, to some extent, by soil salinity. Thus, we attempted to propose that it was likely that the widely distributed desert plants exhibited certain plasticity in water use to access deeper water sources to cope with salt stress in the saline habitats. Similar results were reported that woody plants endured salt stress by spatial partitioning and temporal shift in water absorption in the Everglades ecotone and coastal ecosystems (Ewe et al., 1999, Ewe et al., 2007; Ewe and Sternberg 2002). It has been reported that desert plants may shifted to deeper soil water to suffer salt stress in Xinjiang, northwest China (Min et al., 2019). In this study, soil EC, SO_4^{2-}, Cl^- and Na^+ decreased with soil depths (**Figures 1**, **2**), and soil salinity declined with depths. Salt accumulation in the soil generally change the soil texture and decrease the soil porosity, and consequently reduce the soil aeration and water conductance (Min et al., 2019). Moreover, high soil salinity cause plants access water more difficultly (Mahajan and Tuteja 2005; Yang et al., 2007). Therefore, the ability to explore and utilized deeper water sources ensure these desert plants to acclimate to environments stresses.

CONCLUSION

Our research indicated that niche complementarity for water resources among coexisting desert species is the potential mechanism for water-limited and salinity-effected ecosystems, which could maintain a resilient community under drought stress and salt stress. In each saline site, contrasting soil depths of water use for each desert species were mainly determined by their distinct root distributions, which cause water source partitioning. The studied common plant species would access more deeper soil water in more saline habitat, implying *T. ramosissima* and *A. sparsifolia* had the ability to shift to deeper soil water to suffer salt stress. A better understanding of plants physiological responses to different soil salinities would facilitate to rehabilitate saline soil and provide a scientific basis for ecosystem protection and management in arid and semiarid environment.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.