Journal of Plant Interactions

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tjpi20

Water uptake from different soil depths for halophytic shrubs grown in Northern area of Ningxia plain (China) in contrasted water regimes

Lin Zhu a b, Zheng Hong Wang c, Gui Lian Mao d, Shu Xin Zheng e & Xing Xu a

a State Key Laboratory Breeding Base of Land Degradation and Ecological Restoration of North-western China, Ningxia University, Yinchuan, 750021, China
b State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Water and Soil Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, 712100, China
c Department of Biotechnology, College of Agricultural, Henan University of Science and Technology, Luoyang, 471003, China
d Department of Botany, Life Science College, Ningxia University, Yinchuan, 750021, China
e Department of Agronomy, Agricultural College, Ningxia University, Yinchuan, 750021, China

Accepted author version posted online: 20 Nov 2012. Published online: 12 Dec 2012.

To cite this article: Lin Zhu, Zheng Hong Wang, Gui Lian Mao, Shu Xin Zheng & Xing Xu (2014) Water uptake from different soil depths for halophytic shrubs grown in Northern area of Ningxia plain (China) in contrasted water regimes, Journal of Plant Interactions, 9:1, 26-34, DOI: 10.1080/17429145.2012.751139

To link to this article: http://dx.doi.org/10.1080/17429145.2012.751139

Please scroll down for article

Taylor & Francis makes every effort to ensure the accuracy of all the information (the “Content”) contained in the publications on our platform. Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Versions of published Taylor & Francis and Routledge Open articles and Taylor & Francis and Routledge Open Select articles posted to institutional or subject repositories or any other third-party website are without warranty from Taylor & Francis of any kind, either expressed or implied, including, but not limited to, warranties of merchantability, fitness for a particular purpose, or non-infringement. Any opinions and views expressed in this article are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor & Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

Taylor & Francis and Routledge Open articles are normally published under a Creative Commons Attribution License http://creativecommons.org/licenses/by/3.0/. However, authors may opt to publish under a Creative Commons Attribution-Non-Commercial License http://creativecommons.org/licenses/by-nc/3.0/ Taylor & Francis and Routledge Open Select articles are currently published under a license to publish, which is based upon the Creative Commons Attribution-Non-Commercial No-Derivatives License, but allows for text and data mining of work. Authors also have the option of publishing an Open Select article under the Creative Commons Attribution License http://creativecommons.org/licenses/by/3.0/.
It is essential that you check the license status of any given Open and Open Select article to confirm conditions of access and use.
RESEARCH ARTICLE

Water uptake from different soil depths for halophytic shrubs grown in Northern area of Ningxia plain (China) in contrasted water regimes

Lin Zhu\textsuperscript{a,b}*\textsuperscript{,} Zheng Hong Wang\textsuperscript{c}, Gui Lian Mao\textsuperscript{d}, Shu Xin Zheng\textsuperscript{e} and Xing Xu\textsuperscript{a}

\textsuperscript{a}State Key Laboratory Breeding Base of Land Degradation and Ecological Restoration of North-western China, Ningxia University, Yinchuan 750021, China; \textsuperscript{b}State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Water and Soil Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, China; \textsuperscript{c}Department of Biotechnology, College of Agricultural, Henan University of Science and Technology, Luoyang 471003, China; \textsuperscript{d}Department of Botany, Life Science College, Ningxia University, Yinchuan 750021, China; \textsuperscript{e}Department of Agronomy, Agricultural College, Ningxia University, Yinchuan 750021, China

(Received 30 September 2012; final version received 15 November 2012)

In order to understand the contributions of groundwater and deep soil water to the growth of halophytes in salinity-affected area, water use strategies of four shrubs, i.e. 20-year-old \textit{Tamarix ramosissima} Ledeb., three-year-old \textit{T. ramosissima}, \textit{Lycium barbarum} L., and \textit{Atriplex canescens} (Pursh) Nutt. were studied under contrasted water regimes in Northwest China. The result showed that there was a vertical gradient in soil $\Delta^{18}$O and $\delta$D profiles resulted from evaporation and irrigation. The 20-year-old \textit{T. ramosissima} mainly used water from middle (40–140 cm) and deep (140–200 cm) under both water regimes indicating its phreatophytic nature. Soil water in upper profile (0–40 cm) was the dominant water source for the three-year-old \textit{T. ramosissima} before irrigation. After irrigation, the three-year-old \textit{T. ramosissima} and \textit{L. barbarum} switched their water sources to middle soil profile. Our experiment revealed phreatophytic tendency for the three-year-old \textit{A. canescens}, which was not responsive to irrigation enlighten by photosynthetic parameters and stem water potentials.

\textbf{Keywords:} soil water utilization; stable hydrogen and oxygen isotope; halophytic shrub; Ningxia plain; saline-alkali land

Introduction

For nearly a century, the rooting depths and patterns of plants living in water-limited environments have been the ‘hot point’ for plant physiologists and ecologists. Plant functional type of root system is fundamental in determining their water use strategy and physiological responses to a specific water source (Xu & Li 2006). Different rooting patterns among species have resulted from long-period evolution and served as adaptations minimizing competition for water in a particular habitat (Dawson et al. 1993; Dawson & Pate 1996). The patterns of water uptake by woody species are summarized as either using only deep soil water or tapping both shallow and deep layers (Dodd et al. 1998; Goldstein et al. 2008; Guevara et al. 2010; Williams & Ehleringer 2000; West et al. 2007). On the basis of this finding, a terminology ‘phreatophyte’ (the species that extract water from aquifers or the capillary fringe above the water table) has come into being and has been widely agreed in the academic field (Busch et al. 1992; Eggemeyer et al. 2009; Gries et al. 2003; Lite & Stromberg 2005; Lin et al. 1996; Sperry & Hacke 2002). According to the extent of this dependence, phreatophytes are classified as either ‘obligate’ (plants that utilize only shallow alluvial groundwater) or ‘facultative’ (plants that have the ability to utilize sources in addition to alluvial groundwater) (Busch et al. 1992; Horton et al. 2003). \textit{T. ramosissima} has been listed as facultative phreatophytes, it utilizes only groundwater when this water source is shallow and relatively constant in depth, but is also able to extract water from unsaturated soil by its greater root allocation and physiological adaptability to a higher degree of water stress when groundwater is deeper and temporally more variable in depth (Busch et al. 1992; Busch & Smith 1995; Horton et al. 2001; Smith & Horton 1998). However, the controversial documents are not scarce. Horton et al. (2003) did not find water use from the unsaturated soil by \textit{T. ramosissima} grown in a serious of sites with a groundwater gradient from 0 to 4.4 m. Xu and Li (2006) reported \textit{T. ramosissima} relied mostly on groundwater for survival and did not show a significant photosynthetic response to sustained drought or heavy rain pulse event.

\textit{Atriplex canescens}, known as xerohalophyte, has been reported to have deepest root indices, vulnerable shallow roots, and uniformly high $\psi$ throughout the summer, suggesting preferential use of more stable deep soil water and phreatophytic tendency (Sperry & Hacke 2002).

\*Corresponding author. Email: zhulinscience@126.com

© 2012 Taylor & Francis
The source regions of soil water uptake by plants have traditionally been difficult to assess (Ehrlinger & Dawson 1992) and excavation of roots to determine their spatial distribution is destructive and time consuming (Meinzer et al. 2001). With the development of stable isotope techniques, natural abundance of stable isotopic ratios of hydrogen (6D) and oxygen (818O) has been used as a tracer to determine the source of water extracted from soil by plant (Dawson et al. 1993). The isotopic composition of the soil water may vary with depth. This gradient is related to the isotopic composition of rain water that recharges the soil profiles, the isotopic composition of the groundwater, and the isotopic fractionation occurring during evaporation near the soil surface (Ehrlinger & Dawson 1992; Picon-Cochard et al. 2001). There is no fractionation of water isotopes during root water uptake and transport to the stem. Therefore, the water source of plants can be identified by simultaneously analyzing the isotopic composition of xylem sap and soil water (White et al. 1985; Picon-Cochard et al. 2001).

A large number of reports concentrating on the water source, water use strategy, and plant-water relations of plants using stable isotopic compositions have touched on several ecological systems: riparian areas (Dawson & Ehleringer 1991; Shafroth et al. 2000; Horton et al. 2003; Chimner & Cooper 2004; Lite & Stromberg 2005), desert regions (Sperry and Hacke 2002; Gries et al. 2003; Xu & Li 2006), woodland (Lin et al. 1996; Picon-Cochard et al. 2001), and grassland (Eggemeyer et al. 2009). The information about water use strategies of halophytes, Tamarix ramosissima Ledeb., Atriplex canescens (Pursh) Nutt., and Lycium barbarum L. in salinity- and alkali-affected regions is scarce. Furthermore, the reported researches were conducted at the sites where groundwater table was not beyond the root range of T. ramosissima. Under such circumstance, the conclusion could not be necessarily drawn that T. ramosissima does not use water from upper unsaturated soil.

Yinchuan Plain is located in the southeastern area of Huanghe Alluvial Plain. Huanghe River flows through Yinchuan Plain from southwest to northeast and widespread irrigation web has been well established (Chen et al. 2003). Soil salinity has plagued irrigated lands along the Yellow River in the northern area of Yinchuan Plain shortly after the first canal was built in 214 BC. Such factors, that is, high groundwater table mainly caused by over-irrigation, leaky canals, inadequate drainage system, the flatness of the terrain, and the high level of the Yellow River during the flood season, have contributed to the increase in soil salinity. Low rainfall and strong evaporation also aggravate this ecological problem in this area (Xiong et al. 1996).

In this work, we chose a stand consisting of 3-year-old and 20-year-old T. ramosissima for study the water use strategy of this species. We anticipated that the former one would take up more water in unsaturated soil when its root had not accessed the groundwater, while the latter would mostly rely on groundwater and not responsive to the fluctuating water regimes. The three-year-old Lycium barbarum L. and three-year-old A. canescens inside the stand were also included as check. Irrigation was applied once during the mid-summer for observing the change in water use of the shrubs tested in the contrasted water regimes. The specific objectives of this study are (1) to quantify water uptakes of the shrubs mentioned above from different soil profiles prior to and after irrigation by using 6D and 818O isotopic composition; (2) to evaluate their water use strategies by supplementary measurement of leaf gas exchange parameters and stem water potentials before and after irrigation.

Materials and methods

Site description

The study was conducted in Xidatan, Ningxia, China (1089 m in altitude, 106°30′9″ E, 38°52′33″N). Xidatan is located in the northern area of Yinchuan Plain. Flat terrain makes it difficult for lands to drain water in this area, thus, salinity has arisen. The groundwater table is shallow with salt concentration from 1 g/kg to 3 g/kg. Mean annual rainfall is 172.5 mm, mean annual evaporation is 1755 mm. The groundwater table was 2.5–2.8 m during plant growth period (Zhu et al. 2012).

A stand consisting of three artificially established shrubs, that is, Tamarix ramosissima Ledeb., Atriplex canescens (Pursh) Nutt., and Lycium barbarum L., was established in 2008. Mature Tamarix ramosissima Ledeb. whose age was around 20 years were natively distributed nearby was involved for comparing the age’s effect on water uptake of this species.

One hundred and twenty-millimeter irrigation was applied on 26 June. Irrigation water was pumped from a nearby well.

Water source sampling and analysis

Samples of well water, precipitation water, soil water from different depths, and groundwater were collected for hydrogen and oxygen isotopic analyses; samples were sealed in glass vials with screw caps and wrapped with parafilm. For determination of plant water source, five individuals were chosen at random. Fully suberized branches on the top of canopy were collected from each plant. The barks and green leaves were eliminated from branches, then the samples were immediately sealed in glass vials in the way described above. Rain water samples were collected after precipitation from May to July. Groundwater was sampled in monitoring wells and well water was sampled in a machine well. Samples of soil and stem were kept frozen at −20°C, while rainwater, well water, and groundwater samples were stored at

Journal of Plant Interactions 27
4°C until analysis for hydrogen and oxygen. Samples of soil water, groundwater, and plant water were collected on 28 May and 5 July. Ground-water depth was measured monthly in monitoring wells. Irrigation (120 mm) was applied three days before the second sampling.

For analyzing D and \(^{18}\)O compositions, water in soil and stem was extracted using cryogenic vacuum distillation (Horton et al. 2003). \(\text{H}_2\text{O}\) was split into CO and \(\text{H}_2\) on the effect of catalyst in FLASHEA 1112HT (Thermo Scientific, Germany) isotopic analyzer. DELTA V isotope ratio mass spectrometer (Thermo Scientific, Germany) was used to analyze O in CO and H in \(\text{H}_2\) for obtaining the ratios \(^{18}\text{O}/^{16}\text{O}\) and \(^2\text{H}/^{1}\text{H}\). The \(\delta\text{D}\) and \(\delta^{18}\text{O}\) values were expressed in parts per thousand (%) relative to the V-SMOW standard (Gonfiantini 1978).

\[
\delta\text{D or } \delta^{18}\text{O} = \left[ \frac{R_{\text{sample}}}{R_{\text{reference}}} - 1 \right] \times 1000
\]

where \(R\) is \(^2\text{H}/^{1}\text{H}\) for deuterium, or \(R\) is \(^{18}\text{O}/^{16}\text{O}\) for oxygen.

To determine the fractional contribution of water sources to studied species, the IsoSource program was used (http://www.epa.gov/wed/pages/models/stableIsotopes/isosource/isosource.htm) (Phillips et al. 2005). Totally, there were 11 source endpoints, i.e. 0–5, 5–20, 20–40, 40–60, 60–80, 80–100, 100–120, 120–140, 140–160, 160–180, 180–200 cm, measured from 0 to 200 cm soil profile, which were too many to allow for feasible solutions. Therefore, we combined the data into three layers (0–40, 40–140, and 140–200 cm).

Soil water content and salinity

Volumetric soil water content was determined by time domain reflectometry technology (TDR Trime-T3, Ettlingen/Baden-Württemberg, Germany). For measuring volumetric water content, a probe was inserted into a 2-m plastic tube, buried vertically in the field in advance, and readings were recorded at intervals of 20 cm. Measurement was made at 28 May and 5 July. The soil water content is showed in Figure 2.

Soil soluble salt content was analyzed by dissolving the soil samples into distilled water to achieve a soil solution, and then drying the solution to obtain the salt residue (Xu & Li 2006). Soil pH was determined by pH-3D pH meter (ZhiGuang Co. Ltd., Shanghai, China).

Leaf photosynthesis and stem water potentials

Leaf gas exchange rates were measured with a Ciras-2 infrared gas analyzer (PP System; Hitchin, Hertfordshire, UK) on leaves of representative shrubs covering an area of 1.7 cm\(^2\). Leaves were maintained at right angles to intercept solar radiation. Net photosynthesis (Pn), transpiration rate (Tr), and stomatal conductance (gs) were provided by the apparatus. Three measurements were made per shrub. After measurement, the spinal leaves of Tamarix ramosissima Ledeb. were collected in plastic bags for measuring leaf area by using Photoshop 6.0. Pn, Tr, and gs were revised according to the ratio of leaf area to chamber area of the apparatus. Transpiration efficiency was calculated as Pn/Tr.

Predawn (Bar; 1 h before sunrise) and midday (Bar; 11:30–12:30 h) water potentials were measured for assessing plant water relations. Measurements were made on 28 May (before irrigation) and 4 July (after irrigation). Water potential was determined with a pressure chamber (PMS Instrument Co., Albany, OR, USA) on tree twigs collected from the same individuals that were used for stable isotope measurements.

Statistical analysis

The effects of irrigation treatments and differences between species were tested with factorial ANOVA analyses (GLM procedure of the SAS software package, SAS Institute, Cary, NC, USA), where the F-values were considered statistically significant at the 0.05 level. Pearson phenotypic correlations were calculated to determine the relationship between \(\delta^{18}\text{O}\) and \(\delta\text{D}\) values, water content, salt content, and pH in soil profile.

Result

Environmental parameters

Total precipitation for the study period was 112.1 mm. No effective rain occurred in April. Monthly rainfall was 45.9 mm in May and 49 mm in June (Figure 1). Soil water content increased with depth. Highest soil water content was observed in the 160–180 cm profile. The highest soluble salt content was recorded in the 100–120 cm profile. The upper and deep profiles were characterized by lower soluble salt content. The salt content of groundwater was 1.48 g/L before irrigation and 1.97 g/L after irrigation. The pH values ranged from 7.1 to 8.8 before irrigation and 7–8.3 after irrigation. Higher pH was noted in the profile below 60 cm before irrigation and in the 20–80 cm profile after irrigation. Irrigation had significant effect on water and soluble salt contents in the 0–140 cm profile (Figure 2).

Isotope compositions of different water sources and xylem water of different shrubs

The \(\delta^{18}\text{O}\) of well water was more negative than groundwater. The isotopic composition in the upper profile (<80 cm) fluctuated temporally and spatially. The \(\delta^{18}\text{O}\) values were lower in the deep soil profile (below 140 cm). In the soil profile from 180 to 200 cm, \(\delta^{18}\text{O}\) values of soil water were close to those of groundwater. Generally, isotopic compositions of
groundwater and soil water significantly decreased after irrigation except for a sudden increase in the 80–100 cm profile (Figure 3). The fractionation processes in different water sources and xylem water of shrubs were evaluated by a $\delta^{18}$O–δD graph (Figure 4). Results showed that almost all the samples of soil water and groundwater plotted at the right side of the local meteoric water line in arid area of Northwest China (ANC LMWL) with the latter plotting neared to the LMWL than the former, while the well water plotted on the LMWL indicating the effect of evaporation on different water sources. Lower $\delta^{18}$O and δD values were found for 20-year-old T. ramosissima than the three-year-old shrubs. After irrigation, the $\delta^{18}$O and δD of four shrubs decreased to some extent (Figure 4).

Relationship among δD, $\delta^{18}$O, soil water content, salt concentration, and pH
Significant and positive correlation between δD and $\delta^{18}$O were recorded regardless of irrigation or not. Soil water content was related positively with soil water δD and $\delta^{18}$O before irrigation. Soil salt concentration correlated positively with soil water δD and $\delta^{18}$O after irrigation. Negative relationship was found between soil pH and values of δD and $\delta^{18}$O before irrigation (Table 1).

Water uptake of different water sources for four shrubs
A three-source mixing model was used to determine the fraction of water acquired by shrubs from three ranges of soil depths (0–40 cm, 40–140 cm, and 140–200 cm). As shown by the model, before irrigation, the three-year-old shrubs, i.e., T. ramosissima, L. barbarum, and A. canescens, mainly used soil water from 0 to 40 cm soil profile. The 20-year-old T. ramosissima mostly extracted moisture in the middle and deep soil profiles (below 40 cm). After irrigation, the three-year-old T. ramosissima and L. barbarum obtained most of their water from the 40–140 cm soil profile. Highest dependence on soil moisture in deep soil profile (140–200 cm) was

![Figure 2](image-url)
observed for 20-year-old *T. ramosissima*. Among the three-year-old shrubs, the *A. canescens* exhibited higher water uptake percent from deep soil profile than the other two shrubs regardless of irrigation or not (Table 2).

### Photosynthetic gas exchange parameters xylem water potentials of different shrubs

The net photosynthetic rate (Pn) of the three-year-old *L. barbarum* was higher than other three shrubs regardless of irrigation or not (Figure 5A). Generally, irrigation exerted significant influence on Pn, gs, and Tr of the three-year-old shrubs *T. ramosissima* and *L. barbarum* L. and on Pn of the 20-year-old *T. ramosissima* (Figure 5A–C). No significant response of the three-year-old *A. canescens* in terms of photosynthetic parameters to irrigation was found (Figure 5A–D). Highest gs and transpiration rate (Tr) were found for the three-year-old *L. barbarum* L. after irrigation. The 20-year-old *T. ramosissima* displayed the highest Tr before irrigation. The three-year-old *A. canescens* exhibited the lowest gs and Tr and the highest intrinsic water use efficiency (WUE) no matter being irrigated or not (Figure 5B–D). A slight and significant decrease in Pn/Tr was noted for the three-year-old *L. barbarum* L. after applying irrigation (Figure 5D).

Before irrigation, twig predawn water potential (ψ_pre) differed among species. The 20-year-old *T. ramosissima* displayed the highest ψ_pre. The lowest ψ_pre was recorded for three-year-old *A. canescens* regardless of whether irrigation was applied or not (Figure 5A). Irrigation had significant effects on ψ_pre and twig midday water potential (ψ_mid) of three-year-old *T. ramosissima* and ψ_mid of three-year-old *L. barbarum* and *A. canescens*. No significant effect on twig water potentials of 20-year-old *T. ramosissima* was noted (Figure 5A and B).

### Discussion

Using stable isotopes to determining the water sources for plant transpiration depends on sources of water having different endogenous isotopic compositions (Eggemeyer et al. 2009). The seasonal input of...
moisture into the soil, evaporation in the uppermost surface layers, or differences between bulk soil moisture and groundwater contribute to the isotopic composition of water within soils (Ehrlinger & Dawson 1992). We observed a vertical gradient in soil water $^{18}$O profiles (Figure 3). The $^{18}$O and $\delta$D values in 0–80 cm soil profile fluctuated indicating the multiple influences of the input of irrigational water, precipitation, and evaporation. A negative correlation between soil water content and values of $^{18}$O and $\delta$D in 0–200 cm soil profile (Table 1) indicated the significant effects of evaporation and irrigational event (well water being $^{18}$O and $\delta$D-depleted) on the soil isotopic compositions. Slight more negative $^{18}$O values were found in deep soil profiles than groundwater, reflecting the combinational effects of irrigations applied in current or previous seasons and the recharge of groundwater to the corresponding soil profiles.

Variations in depth of water uptake for different shrubs before irrigation

Prior to irrigation, the three-year-old shrubs mostly extracted water from upper profile (0–20 cm), while the 20-year-old T. ramosissima mainly used soil water in the middle and deep profiles, reflecting the effects of species and age on the water use strategy of shrubs tested. The three-year-old T. ramosissima was recorded by more negative water potential suggesting it was experiencing strong water stress due to low water content in the upper soil profiles. Presumably, the roots of three-year-old T. ramosissima have not been developed enough to access water in the deeper soil layers during seedling stage, its growth would highly depend on moisture in the upper soil profile through greater capacity in osmotic adjustment (Busch & Smith 1995; Stromberg et al. 1996; Horton et al. 2003). In contrast, the 20-year-old T. ramosissima mostly used deeper soil water by developing active

Table 1. Relationship among soil water hydrogen and oxygen composition, soil water content, soil salt content and pH.

<table>
<thead>
<tr>
<th>Soil water $\delta$D</th>
<th>Soil water $^{18}$O</th>
<th>Soil water $\delta$D</th>
<th>Soil water $^{18}$O</th>
</tr>
</thead>
<tbody>
<tr>
<td>BI</td>
<td>AI</td>
<td>BI</td>
<td>AI</td>
</tr>
<tr>
<td>$\delta$D BI</td>
<td>1.00</td>
<td>$\delta$D AI</td>
<td>1.00</td>
</tr>
<tr>
<td>$^{18}$O BI</td>
<td>0.99**</td>
<td>$^{18}$O AI</td>
<td>1.00</td>
</tr>
<tr>
<td>$\delta$D BI</td>
<td>0.04</td>
<td>$\delta$D AI</td>
<td>0.91**</td>
</tr>
<tr>
<td>$^{18}$O BI</td>
<td>-0.66*</td>
<td>$^{18}$O AI</td>
<td>0.93**</td>
</tr>
<tr>
<td>$\delta$D BI</td>
<td>-0.69*</td>
<td>$\delta$D AI</td>
<td>0.72**</td>
</tr>
<tr>
<td>$^{18}$O BI</td>
<td>-0.38</td>
<td>$^{18}$O AI</td>
<td>0.55</td>
</tr>
<tr>
<td>$\delta$D BI</td>
<td>0.02</td>
<td>$\delta$D AI</td>
<td>0.58*</td>
</tr>
<tr>
<td>$^{18}$O BI</td>
<td>-0.64*</td>
<td>$^{18}$O AI</td>
<td>0.06</td>
</tr>
<tr>
<td>$\delta$D BI</td>
<td>-0.68*</td>
<td>$\delta$D AI</td>
<td>-0.06</td>
</tr>
</tbody>
</table>

Note: Asterisk represents the significance of coefficient, *P < 0.05, **P < 0.01. BI and AI represent before irrigation and after irrigation.

Table 2. Water uptake rate of potential sources for four shrubs in Xidatan (mean (minimum–maximum)).

<table>
<thead>
<tr>
<th>Water sources</th>
<th>20-year-old Tamarix ramosissima, Ledeb.</th>
<th>3-year-old Tamarix ramosissima Ledeb.</th>
<th>3-year-old Lycium barbarum L.</th>
<th>3-year-old Atriplex canescens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before irrigation (May 28)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil depth (cm)</td>
<td>0–40</td>
<td>6.39</td>
<td>10.9 (0–24)</td>
<td>90.6 (85–99)</td>
</tr>
<tr>
<td>Soil depth (cm)</td>
<td>40–140</td>
<td>8.96</td>
<td>46.8 (0–100)</td>
<td>5.1 (0–15)</td>
</tr>
<tr>
<td>Soil depth (cm)</td>
<td>140–200</td>
<td>9.47</td>
<td>42.4 (0–87)</td>
<td>4.2 (0–13)</td>
</tr>
<tr>
<td>After irrigation (July 4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil depth (cm)</td>
<td>0–40</td>
<td>9.79</td>
<td>34.0 (0–83)</td>
<td>6.0 (0–18)</td>
</tr>
<tr>
<td>Soil depth (cm)</td>
<td>40–140</td>
<td>8.60</td>
<td>36.4 (17–56)</td>
<td>88.8 (82–100)</td>
</tr>
<tr>
<td>Soil depth (cm)</td>
<td>140–200</td>
<td>9.97</td>
<td>29.6 (0–72)</td>
<td>5.2 (0–16)</td>
</tr>
</tbody>
</table>
absorbing roots at depths close to the groundwater table (Xu & Li 2006).

Sperry and Hacke (2002) reported that *A. Canescens* exhibited phreatophytic tendency and had deepest root indices and vulnerable shallow root (Lin et al. 1996). Lin et al. (1996) observed *A. canescens* experienced negative predawn and midday water potentials that were not relieved by summer rain indicating less uptake of rain. In our study, higher uptake rate from deep soil profile, and less responses of photosynthetic activity and plant water relations to irrigation for the *A. canescens* were consistent with the above reports.

Higher leaf intrinsic water use efficiency (Pn/Tr) of *A. canescens* agreed with the previous reports that *A. canescens* has C4 photosynthetic path allowing it to remain photosynthetic activity with a greater water use efficiency (Lin et al. 1996).

**Variations in depth of water uptake for different shrubs after irrigation**

After irrigation, a significant decrease in the values of 8D and 818O above 80 cm soil profile suggested the infiltration of well water (with more negative isotopic composition). Significant and positive correlations

![Graph 1](https://example.com/graph1.png)

**Figure 5.** Net photosynthetic rate (Pn), stomatal conductance (gs), transpiration rate (Tr), and intrinsic water use efficiency (Pn/gs) of four shrubs measured before irrigation (28 May) and after irrigation (4 July), 2010 (mean ± SD; n = 6). Different capital letters and lowercases represent significant differences among different measuring times (p < 0.05 and p < 0.01), respectively.

![Graph 2](https://example.com/graph2.png)

**Figure 6.** Twig predawn (Ψpre, A) and midday (Ψmid, B) water potentials of four shrubs measured before irrigation (28 May) and after irrigation (4 July), 2010 (mean ± SD; n = 5). Different capital letters and lowercases represent significant differences among different measuring times (p < 0.05 and p < 0.01), respectively.
meyer et al. (2009) and the replacement of ‘old soil profile after irrigation (Tang & Feng 2001; Eggemeyer et al. 2009) and the replacement of ‘old soil water’ with new infiltrating water would recompose the soil isotopic profile. Presumably, being pushed by irrigation water, the upper soil water (δD and δ18O-enriched) would move downwardly and stop at a certain soil layer, around 100 cm in depth, when the hydraulic gradient exhausted, enhancing the isotopic composition of this layer. A redistribution of the soil salt concentration in the whole soil profile after irrigation was noted, with and inflexion at depth of 100 cm, suggesting an obvious leaching effect on salt concentration profile.

To be unexpected, the highest values of δD and δ18O appeared in the 80–100 cm soil profile. This implied that a ‘piston flow’ might happened in soil profile after irrigation (Tang & Feng 2001; Eggemeyer et al. 2009) and the replacement of ‘old soil water’ with new infiltrating water would recompose the soil isotopic profile. Presumably, being pushed by irrigational water, the upper soil water (δD and δ18O-enriched) would move downwardly and stop at a certain soil layer, around 100 cm in depth, when the hydraulic gradient exhausted, enhancing the isotopic composition of this layer. A redistribution of the soil salt concentration in the whole soil profile after irrigation was noted, with and inflexion at depth of 100 cm, suggesting an obvious leaching effect on salt concentration profile.

Since the irrigation events occurred frequently in the neighbor fields (mostly paddy field) during our second sampling time (4 July), the isotopic compositions of groundwater, being recharged by the δD and δ18O-depleted well water, were more negative than before irrigation. The values of δD and δ18O in the deep profile that approached to groundwater also decreased on 4 July compared with 28 May, which may be accounted for by the effect of capillarity in the area above the aquifer.

In this study, the highest deep soil water uptake percentage was observed for the 20-year-old *T. ramosissima*. No irrigation effect was found on its *Pn*, *gs*, *Tr*, *ψpre*, *ψmid* of uncovering some physiological bases in relation to its phreatophytic nature (Cleverly et al. 1997; Xu & Li 2006). Compared with the 20-year-old *T. ramosissima*, the three-year-old *T. ramosissima* depended heavily on soil water in the middle profile (80–140 cm), implying the age effect on water use strategy of this species. Considering the root of *T. ramosissima* during seedling stage did not approach groundwater layer, it would mainly absorbed moisture from the middle profile where water content was high after irrigation (Figure 2). This fact also reflected the flexible water use strategy of this species. Our experimental result partly corrected some findings of previous reports that *T. ramosissima* only used deep soil water on the ground that this species mostly uses groundwater during mature stage and use other water sources when groundwater is beyond of its root range.

In the present study, *A. canescens* used more water in the deep profile after applying irrigation, revealing its phreatophytic tendency and deep root distribution (Sperry & Hacke 2002). The non-significant increment in *gs* and *Tr* for *A. canescens* after irrigation suggests this plant relies mainly on stable water source – groundwater and remains unresponsive to irrigation.

**Conclusion**

A vertical gradient in soil water δ18O profiles was observed. Evaporation and irrigation have exerted significant effects on soil water oxygen and hydrogen compositions in soil profiles. The three-year-old *Tamarix ramosissima* Ledeb. exhibited flexible water use strategy: utilize water from upper unsaturated soil profile during dry period before irrigation and switched its water use to middle soil profile after irrigation. The 20-year-old *T. ramosissima* heavily depended on middle and deep soil water and was unresponsive to irrigation event. Considering the performances of *T. ramosissima* in different ages, this species is facultative phreatophyte using multiple water sources.

**Acknowledgements**

This study has been financially supported by the National Natural Science Foundation of China (31160478), National Key Technology Research and Development Program of China (2011BAC07B03), Key Project of Chinese Ministry of Education (211195), Open Fund of State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau (10501-287), Ningxia Natural Science Fund (NZ1142), The National Program on Key Basic Research Project of China (2012CB723206). The authors are thankful to the National Natural Science Foundation Committee, Ministry of Science and Technology of China, State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Water and Soil Conservation, Chinese Academy of Sciences and Ministry of Water Resources, for financial support.

**References**


Horton JL, Hart SC, Kolb TE. 2003. Physiological condi-
Guevara A, Giordano CV, Aranibar J, Quiroga M, Villagra
Gries D, Zeng F, Foetzki A, Arndt SK, Bruelheide H,
Gonfiantini R. 1978. Standards for stable isotope measure-
Goldstein G, Meinzer FC, Bucci SJ, Scholz FG, Franco
Ehrlinger JR, Dawson TE. 1992. Water uptake by plants:
Eggemeyer KD, Awada T, Harvey FE, Wedin DA, Zhou
Gonfiantini R. 1978. Standards for stable isotope measure-