Identification of dominant plant water-use strategies in arid zones under deuterium depletion conditions Postprint

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Abstract

Identifying plant water sources is fundamental for elucidating ecohydrological processes and improving water resource management in arid zones under climate change. Stable hydrogen and oxygen isotopes are commonly used to trace plant water uptake; however, cryogenic vacuum extraction (CVE), the standard method for extracting plant xylem water, may induce deuterium depletion, thereby biasing source attribution. To systematically assess the effects of CVE-induced deuterium depletion across species, size classes, and habitats, we excavated five representative soil profiles along the mainstream of the Tarim River in northwestern China, in mid-July 2022. A total of 29 individuals, comprising both Populus euphratica and Tamarix ramosissima, were sampled. We divided P. euphratica individuals into four groups based on diameter at breast height (<50, 50-100, 100-250, and >250 cm), while categorized T. ramosissima individuals into four groups according to plant height (<1.0, 1.0-2.0, 2.0-4.0, and >4.0 m). Plant xylem water was extracted using CVE, and five deuterium depletion scenarios (-5.00‰, -7.00‰, -9.00‰, -11.00‰, and -13.00‰) were simulated. The Bayesian Mixing Model for Stable Isotope Analysis in R (MixSIAR) was applied under six input modes to quantify the proportional contributions of potential water sources and associated prediction errors. Model evaluation revealed that P. euphratica achieved the highest accuracy with a -9.00‰ correction of depletion, whereas a -11.00‰ correction was optimal for T. ramosissima, reducing relative prediction errors by 68.65% and 67.73%, respectively, compared with uncorrected scenario. Small-sized P. euphratica individuals exhibited less deuterium depletion, whereas no clear size-dependent pattern was observed for T. ramosissima. Spatially, plant individuals located farther from the river exhibited reduced deuterium depletion in xylem water. Despite differences in species traits and habitat conditions, both species predominantly

relied on deep soil water and groundwater, which together contributed, on average, 61.45% and 59.95% for P. euphratica and T. ramosissima, respectively. These findings highlight the necessity of accounting for CVE-induced deuterium depletion when identifying plant water-use strategies and provide methodological guidance for isotope-based ecohydrological studies in arid environments.

Full Text

Preamble

J Arid Land (2026) 18(4): 676–695 Identification of dominant plant water-use strategies in arid zones under deuterium depletion conditions DAI Ningze 1,2,3 , SHI Fengzhi 1,2,3* , WANG Yuehui , YAO Peng 1,2,3 , ZHU Jianting ZHAO Chengyi 1 State Key Laboratory of Desert and Oasis Ecology, Key Laboratory of Ecological Safety and Sustainable Development in Arid Lands, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China; Aksu National Station of Observation and Research for Oasis Agro-ecosystem, Aksu 843017, China; University of Chinese Academy of Sciences, Beijing 100049, China; Key Laboratory of Surficial Geochemistry, Ministry of Education, Department of Hydrosciences, School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China; Department of Civil and Architectural Engineering, University of Wyoming, Laramie, WY 82071, USA; School of Geographical Sciences, Nanjing University of Information Science & Technology, Nanjing 210044, China

Abstract

Identifying plant water sources is fundamental for elucidating ecohydrological processes and improving water resource management in arid zones under climate change. Stable hydrogen and oxygen isotopes are commonly used to trace plant water uptake; however, cryogenic vacuum extraction (CVE), the standard method for extracting plant xylem water, may induce deuterium depletion, thereby biasing source attribution. To systematically assess the effects of CVE-induced deuterium depletion across species, size classes, and habitats, we excavated five representative soil profiles along the mainstream of the Tarim River in northwestern China, in mid-July 2022. A total of 29 individuals, comprising both Populus euphratica Tamarix ramosissima , were sampled. We divided P. euphratica individuals into four groups based on diameter at breast height (<50, 50–100, 100–250, and >250 cm), while categorized T. ramosissima individuals into four groups according to plant height (<1.0, 1.0–2.0, 2.0–4.0, and >4.0 m). Plant xylem water was extracted using CVE, and five deuterium depletion scenarios (-5.00‰, -7.00‰, -9.00‰, -11.00‰, and -13.00‰) were simulated. The Bayesian Mixing Model for Stable Isotope Analysis in R (MixSIAR) was applied under six input modes to quantify the proportional contributions of potential water sources and associated prediction errors. Model evaluation revealed that P. euphratica achieved the highest accuracy with a –

9.00‰ correction of depletion, whereas a -11.00‰ correction was optimal for T. ramosissima , reducing relative prediction errors by 68.65% and 67.73%, respectively, compared with uncorrected scenario. Small-sized euphratica individuals exhibited less deuterium depletion, whereas no clear size-dependent pattern was observed for T. ramosissima . Spatially, plant individuals located farther from the river exhibited reduced deuterium depletion in xylem water. Despite differences in species traits and habitat conditions, both species predominantly relied on deep soil water and groundwater, which together contributed, on average, 61.45% and 59.95% for P. euphratica T. ramosissima , respectively. These findings highlight the necessity of accounting for CVE-induced deuterium depletion when identifying plant water-use strategies and provide methodological guidance for isotope-based ecohydrological studies in arid environments.

Keywords

plant water uptake; hydrogen isotopes; oxygen isotopes; cryogenic vacuum extraction (CVE); deuterium depletion; Bayesian Mixing Model for Stable Isotope Analysis in R (MixSIAR); Tarim River Basin

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1 Introduction

The stability of arid ecosystems is highly dependent on groundwater resources (Dean, 2019; Li et al., 2024). Numerous studies have demonstrated that shallow groundwater functions as a vital water source for plant survival in arid zones (Eamus et al., 2006; Glanville et al., 2023). In arid environments, plant water sources extend beyond soil water (Loheide II et al., 2005). Under conditions of soil water scarcity, plants often develop deeper and more complex root systems to access groundwater directly (Canadell et al., 1996). Riparian plants in these environments have evolved various adaptive strategies—such as adjusting root distribution patterns, regulating transpiration rates, and maintaining hydraulic connectivity between roots and groundwater—to sustain water uptake during drought periods to cope with fluctuations in river flow and soil moisture (Horton et al., 2001a; Stromberg, 2013). Studies have reported that in the arid zones of Xinjiang Uygur Autonomous Region, China, dominant riparian species, such as Populus euphratica Tamarix ramosissima , rely on a combination of shallow soil water and deep groundwater, exhibiting clear species-specific differences in rooting depth and seasonal water uptake patterns (Dai et al., 2025; Jiang et al., 2025). Li et al. (2019) indicated that although both species share certain responses to groundwater fluctuations, they also display notable distinctions.

Specifically, both species reduce daily water use as drought intensifies; however, T. ramosissima more rapidly adjusts its hydraulic traits to maintain water uptake, whereas P. euphratica exhibits a more pronounced trade-off between growth and water allocation. Xu et al. (2024) further suggested that T. ramosissima possesses high plasticity in water-use strategies, enabling it to shift its root water uptake from shallow soil layers to deeper strata and ultimately to groundwater as aridity increases. These findings highlight the complex interactions between plant functional traits and variable water availability in arid inland river basins. Over the past decade, groundwater depth in arid zones has declined due to human activities and climate change, contributing to the degradation of groundwater-dependent ecosystems and shifts in vegetation patterns (Chen et al., 2019; Yang et al., 2019; Rohde et al., 2024; Guo et al., 2025). Therefore, identifying dominant plant water sources and elucidating the interactions between plants and groundwater represent key scientific challenges in ecohydrological research within arid inland river basins (Orellana et al., 2012; Wang et al., 2023).

Stable isotope tracing of water is a widely used method for identifying plant water sources (Yang et al., 2015; Gai et al., 2023). When potential water sources available to plants exhibit distinct stable hydrogen and oxygen isotopic signatures (Deng et al., 2017) and when isotopic fractionation during plant water uptake and internal transport is assumed negligible (Ehleringer and Dawson, 1992), this approach can be used to estimate the proportional contribution of each source to plant water use. However, studies have shown that cryogenic vacuum extraction (CVE), which has long been considered as the standard technique for plant water isotope analysis, can lead to a significant deuterium depletion in extracted plant water, while the associated bias in oxygen isotope ratio (δ O) is typically minor and often negligible (Zhao et al., 2016; Yang et al., 2025). Chen et al. (2020) designed an experimental system to independently measure the deuterium isotope ratio (δD) values of xylem water and potential water sources of plants, reporting that deuterium depletion ranged from -12.20‰ to -7.40‰. Similarly, Cai et al. (2024) concluded that explicitly accounting for deuterium depletion (from -11.90‰ to -4.60‰) markedly reduces prediction errors and enhances the reliability of plant water source apportionment. Neglecting this depletion can substantially bias the interpretation of plant water sources, leading to the overestimation of deep-water use. This depletion phenomenon is influenced by plant species and water status (Wen et al., 2022) and is further impacted by plant size and the surrounding growth environment (Tao et al., 2025). In addition, studies have indicated that CVE can introduce isotopic biases during soil water extraction; however, these

biases can be corrected using indirect methods, such as empirical corrections based on soil texture and water content, comparisons with vapor equilibration or centrifugation techniques, and post-extraction isotope offset adjustments (Orlowski et al., 2016; Wen et al., 2021).

Isotope mixing models estimate the proportional contribution of different water sources to plant water uptake based on the input isotope values of various water sources and plant xylem water.

Commonly used models include the IsoSource and several Bayesian mixing models, such as Mixing Models Using Stable Isotope Ratios (MixSIR), Stable Isotope Analysis in R (SIAR), and Mixing Models for Stable Isotope Analysis in R (MixSIAR). The IsoSource model, based on mass balance, is applicable when the number of sources is less than or equal to the number of isotopes; however, it cannot account for measurement uncertainty or source variability, often yielding ambiguous results due to the absence of probabilistic weighting (Phillips and Gregg, 2003).

MixSIR incorporates a Bayesian framework with a Markov Chain Monte Carlo (MCMC) approach, which can enable the quantification of uncertainty in source contributions and improve estimation accuracy (Moore and Semmens, 2008). The SIAR model, implemented in the R software, handles multi-source and multi-isotope data, accounting for both measurement errors and source variability and offering greater flexibility (Phillips et al., 2014). MixSIAR integrates the advantages of MixSIR and SIAR by incorporating fixed and random effects, process and residual errors, and multiple sources of uncertainty, thereby enhancing its accuracy in estimating plant water sources and their relative contributions (Stock et al., 2018). It is considered superior to the IsoSource model and other Bayesian mixing models (Wang et al., 2019; Zhou et al., 2021; Cai et al., 2024). Nevertheless, uncertainties in input data can lead to varying predictions across isotope mixing models (Jackson et al., 2009; Layman et al., 2012), highlighting the need to carefully address CVE-induced deuterium depletion and adopt scientifically sound classifications of potential water sources. Most studies have defined soil water layers based on fixed depths (e.g., Zhou et al., 2021; Cai et al., 2024); however, in arid zones where vertical gradients in soil moisture content are pronounced, such depth-based partitioning may obscure the key mechanisms of interactions among groundwater, soil water, and plant water, thereby increasing prediction errors (Sprenger et al., 2019). In arid environments, capillary rise is critical for plant water acquisition (Naumburg et al., 2005). The strong hydraulic connectivity between groundwater and deep soil water, driven by capillary action, suggests that explicitly accounting for this process would help improve the accuracy and interpretability of soil water layer classification.

In this study, we selected five soil profiles along the upper, middle, and lower reaches of the mainstream of the Tarim River in Xinjiang, China to enhance the accuracy of attributing plant water sources under diverse habitat conditions and vegetation characteristics in arid zones.

Around each soil profile, the plant individuals of varying sizes from two dominant species, i.e., euphratica T. ramosissima , were sampled. We found that the δD values of plant xylem samples exhibited deuterium depletion caused by CVE. In response, Bayesian MixSIAR, which is based on stable isotope segmentation techniques, was employed to trace plant water sources. We further

Figure 1

Figure 1: Figure 1

compared the model performance metrics under different assumed deuterium depletion levels and ensured that the optimal deuterium depletion values for both species fell within the preset interval, while verifying the rationality of accounting for CVE-induced deuterium depletion. Consequently, our research enables a more accurate estimation of water source contributions and advances the understanding of the strategies needed for using deuterium-depleted water in arid ecosystems. 2 Materials and methodology

2.1 Study area

The study area is located along the mainstream of the Tarim River in China, covering a river reach of approximately 1321.00 km. It spans longitudes from 80°49$ '12' '*Eto*88°58' 48' '*Eandlatitudesfrom*39°18' 36' '*Nto*41°48' 36'' $N (Fig. 1

). The region lies in an extremely arid zone, where the

water supply primarily depends on glacial meltwater and precipitation originating from the Tianshan Mountains and Kunlun Mountains. River discharge exhibits strong seasonality, with higher flows during summer due to increased glacial meltwater and precipitation, and reduced or intermittent flows during winter. The region has a warm, temperate continental climate, characterized by intense aridity and high evaporation. The mean annual precipitation ranges from 17.4 to 42.0 mm, whereas the mean annual potential evapotranspiration ranges from 2500.0 to 3000.0 mm (Zhou et al., 2024). The soil mainly consists of silt and sand. Desert riparian vegetation is primarily distributed along the Tarim River, with P. euphratica T. ramosissima being the dominant species; their growth and development rely on surface runoff and groundwater. The P. euphratica forest in the Tarim River Basin represents the most well-preserved and extensive distribution of this species in China and holds significant ecological value at the global scale (Keram et al., 2021; Zou et al., 2024).

Overview of the study area based on the digital elevation model (DEM; a), and field photographs showing the soil profiles at Alaer (b), Ermuchang (c), Yingbazha (d), Aqike (e), and Yingsu (f)

2.2 Sampling and isotope analyses

Five soil profiles were excavated along the mainstream of the Tarim River from upstream to downstream at the Alaer, Ermuchang, Yingbazha, Aqike, and Yingsu profiles (Fig. 1) in mid-July 2022. From Alaer to Yingsu, the profiles were located at distances of 1.10, 1.75, 4.10, 17.50, and 25.50 km from the river channel, corresponding to the groundwater depths of 2.8, 2.8, 2.4, 3.0, and

3.0 m, respectively. At each profile, undisturbed soil samples were collected at 20.0 cm intervals from the surface down to the local water table, yielding 15, 15, 13, 16, and 16 sampling intervals at the Alaer, Ermuchang, Yingbazha, Aqike, and Yingsu profiles, respectively. At each soil depth, two replicates were collected: one was sealed in vials with sealing film and stored on

dry ice for the subsequent stable isotope analysis of soil water, and the other was used to determine volumetric water content and soil texture. In total, 30 soil samples were collected from each of the Alaer and Ermuchang profiles, 32 from each of the Aqike and Yingsu profiles, and 26 from the Yingbazha profile.

A total of 15 P. euphratica and 14 T. ramosissima trees of varying sizes, with intact canopies, normal leaf coloration, and no visible signs of disease or mechanical damage, were sampled across the five profiles between 17 and 26 July, 2022. For each tree, sun-exposed, lignified branch segments (5.0–10.0 cm in length and 0.5–1.5 cm in diameter) were collected using ethanol-cleaned pruning shears. In the field, the outer bark and phloem were immediately removed with a clean stainless-steel blade to minimize contamination from nonxylem tissues.

Samples were briefly rinsed with deionized water to remove surface dust and gently blotted dry with lint-free tissue. To ensure reproducibility and quantify within-individual variability, we collected xylem samples in triplicate from three branches of each tree, resulting in a total of 87 samples. All samples were placed into pre-labelled, air-tight glass vials with minimal headspace, sealed immediately, and stored in a portable cooler with ice packs in the field. Upon return to the laboratory on the same day, the collected xylem samples were transferred to a -20°C freezer and kept frozen until CVE and subsequent isotope analysis. Owing to the differences in life form between trees and shrubs, we categorized P. euphratica individuals into four groups based on diameter at breast height (DBH): <50 cm (P1), 50-100 cm (P2), 100-250 cm (P3), and >250 cm (P4), and divided ramosissima individuals into four groups by plant height: <1.0 m (T1), 1.0-2.0 m (T2), 2.0-4.0 m (T3), and >4.0 m (T4) (Table 1).

Additionally, groundwater and surface water samples were collected from each profile. In total, 113 groundwater samples and 38 surface water samples—drawn from the main channel adjacent to the sampling locations—were collected across the study area for isotope analysis. The spatial distribution of all sampling profile points is shown in Figure 1.

The soil and frozen plant xylem samples designated for isotope analysis were sent to the Shenzhen Huake Precision Stable Isotope Laboratory, Shenzhen, China, for measurement of the δD and δ O values. Water was extracted from the soil and frozen plant xylem samples using a cryogenic vacuum distillation system (LI-1200 Automatic Vacuum Water Extraction System; Beijing LICA United Technology Limited, Beijing, China), following an internal laboratory standard operating procedure.

Isotope analyses were performed using a Thermo Scientific DELTA V Isotope

Ratio Mass Spectrometer coupled with a Thermo Scientific Flash 2000 HT Elemental Analyzer (Thermo Fisher Scientific, Waltham, USA), following an internal laboratory standard operating procedure.

The stable hydrogen and oxygen isotope compositions (δD and δ O) of the samples were determined accordingly. The δD and δ O values of the water samples were calculated using Equation 1, following the method of Craig (1961): where δ denotes the stable isotope composition of hydrogen or oxygen (‰), expressed in delta notation relative to that of the reference standard. Specifically, δ represents δD or δ O, and are the isotope ratios (D/H or O) of the sample and the reference standard, respectively. The Vienna Standard Mean Ocean Water was used as the reference standard in this study. 2.3 Preset deuterium depletion values and partitioning of potential plant water sources

2.3.1 Preset deuterium depletion values

Previous studies have reported that deuterium depletion in plant xylem water typically ranges from -12.20‰ to -7.40‰ or from -11.90‰ to -4.60‰ (Chen et al., 2020; Cai et al., 2024).

Several factors, including plant species, individual size, and environmental conditions, influence this isotope offset. To date, however, no species-specific reference values for deuterium depletion have been established for P. euphratica T. ramosissima due to CVE. Therefore, based on the

Plant sampling information Plant type Group Profile DBH (cm) Height (m) Populus euphratica Tamarix ramosissima Alaer Ermuchang Ermuchang Yingbazha Yingsu Yingsu Yingsu Note: DBH stands for diameter at breast height. P1-P4 represent four groups of P. euphratica individuals based on DBH: <50, 50-10, 100-250, and >250 cm, respectively. T1-T4 represent four groups of T. ramosissima individuals based on plant height: <1.0, 1.0-2.0, 2.0-4.0, and >4.0 m, respectively. The symbol ' '/' ' denotes no data available. measured data of this study, we evaluated model performance using the root mean square error (RMSE), mean absolute percentage error (MAPE), and Nash-Sutcliffe efficiency (NSE) under different assumed deuterium depletion levels, to identify a reasonable depletion range from -13.00‰ to -5.00‰. This approach ensured that the optimal depletion values for both species fell within the preset interval while verifying the rationality of accounting for CVE-induced deuterium depletion. In this study, only δD depletion was considered, whereas δ O values in plant xylem water were not adjusted.

In addition to its effects on the δD values of plant xylem water, CVE can bias δD and δ measurements in soil water; however, this bias can be corrected indirectly. Wen et al. (2021) developed empirical correction equations for the CVE-induced isotope deviation ($\Delta\delta$; ‰) in soil water, using soil water content and clay content as predictor variables. The correction equation is

expressed as follows: where CC is the clay content (g/g); SWC is the soil water content (g/g); and , and are the empirically fitted parameters (for δD, = -5.99, = -5.33, and =21.64; for δ = -0.45, = -0.86, and =1.86). The corresponding determination of coefficient ( ) values are 0.84 and 0.60, and the mean error values are all close to zero. The RMSEs for $\Delta\delta$D and $\Delta\delta$ O are 0.66‰ and 0.12‰, respectively (Wen et al., 2021).

In this study, the correction equation was applied to adjust the δD and δ O values of soil water for CVE-induced bias. Subsequently, the corrected values were used in the isotope mixing model to quantify plant water sources.

Classification of potential plant water sources An accurate classification of potential water sources is essential when applying stable isotope techniques to quantify plant water uptake, as it directly affects both the number of sources included in the model and the associated isotope inputs. Although MixSIAR can theoretically accommodate an unlimited number of sources, preliminary tests revealed that including more than five sources can result in highly uniform source contributions and reduce model reliability. To enhance model performance, we divided potential water sources into four categories: groundwater, deep soil water, mid-depth soil water, and shallow soil water. The depth ranges of these categories were determined using their measured stable isotope profiles and the estimated capillary rise height of soil water, as detailed in the following section.

Given that capillary rise height varies with soil texture, we referred to the ternary contour maps of capillary rise height provided in Yang et al. (2020), which were generated from projection pursuit regression model-based simulations using clay, silt, and sand contents as input parameters. The maximum relative error of this method was 17.20%, with most errors below 5.00%. Based on these data, we estimated the capillary rise heights at the Alaer, Ermuchang, Yingbazha, Aqike, and Yingsu profiles being 1.0, 0.6, 1.2, 0.6, and 1.0 m, respectively. The soil water within the capillary fringe, i.e., from the water table up to the estimated capillary rise height, defined as deep soil water and hydraulically connected to groundwater, was considered the first potential plant water source. In the surface layers, intense evaporative demand in arid environments leads to substantial isotope enrichment and variability. This surface-affected zone exhibited significantly different isotope signatures from those of deeper layers (<0.05) and was defined as shallow soil water, representing the second potential water source. Based on isotope data, we determined the depth ranges of shallow soil water to be 0.0-0.6, 0.0-0.2, 0.0-0.4, 0.0-0.4, and 0.0-0.8 m at the Alaer, Ermuchang, Yingbazha, Aqike, and Yingsu, respectively.

The soil water between the shallow and deep layers, characterized by relatively stable δD and O values, was classified as mid-depth soil water, representing the third potential plant water source. Finally, the groundwater samples collected from each profile were designated the fourth potential plant water source.

2.4.1 Bayesian MixSIAR

To quantify the relative contributions of potential water sources to P. euphratica ramosissima , we employed the Bayesian MixSIAR model (Stock et al., 2018), which accounts for uncertainty from multiple sources, incorporates prior information, and supports both fixed and random effects to model variability in source contributions. Model inputs included the means and standard deviations of δD and δ O values for each potential water source and plant xylem water.

Considering that water uptake is generally nonfractionating, both the concentration dependence and trophic discrimination factor were set to zero. MCMC iterations were set to the " extreme'' level to ensure model convergence, and the error structure was specified as " residual only'' . Final outputs were reported as the mean proportional contribution of each water source (Zhou et al., 2021; Cai et al., 2024).

2.4.2 Data inputs for Bayesian MixSIAR model The model was operated using δD and δ O values from groundwater, CVE-corrected soil water, and plant xylem water. For plant xylem water, only δD was adjusted because the δ O offset is generally negligible. In contrast, both δD and δ O values of soil water were corrected.

Adjustments were applied for five preset levels of deuterium depletion. To assess the effects of deuterium depletion on source partitioning, we also included a control scenario without deuterium depletion adjustment. A dual-isotope (δD and δ O) approach was employed across all six correction scenarios: (1) F0—original δD and δ O values; (2) F5—δD and δ O values were adjusted for -5.00‰ deuterium depletion; (3) F7—δD and δ O values were adjusted for -7.00‰ deuterium depletion; (4) F9—δD and δ O values were adjusted for -9.00‰ deuterium depletion; (5) F11—δD and δ O values were adjusted for -11.00‰ deuterium depletion; and (6) F13—δD and δ O values were adjusted for -13.00‰ deuterium depletion. These scenarios enabled a systematic evaluation of the sensitivity of water source attribution to varying assumptions about deuterium depletion of plant xylem water.

Evaluation of model performance We evaluated the prediction errors of different correction scenarios by comparing the observed stable isotope values of plant xylem water with the weighted sum of the stable isotope values of each water source and its corresponding contribution proportion estimated by the Bayesian MixSIAR model. Specifically, the predicted stable isotope value was calculated as the sum of the products of the contribution ratios and the stable isotope values of each potential water source, expressed using Equations 3-5 as follows:

1 A

B C D f f f f = + + + , (4)

δ' δ δ p o Δ = − , (5)

Figure 2

Figure 2: Figure 2

where δ represents the predicted stable isotope (δD or δ O) value of plant xylem water (‰); δ represents the observed isotope (δD or δ O) value of plant xylem water (‰); δ , and δ represent the stable isotope values (either δD or δ O) of shallow soil water, mid-depth soil water, deep soil water, and groundwater (‰), respectively; , and represent the contribution proportions of shallow soil water, mid-depth soil water, deep soil water, and groundwater sources estimated by the Bayesian MixSIAR model (%), respectively; and $\Delta\delta$' represents the prediction error of different correction scenarios (‰), i.e., isotope difference between the predicted stable isotope value (δ) and the observed stable isotope value (δ We further adopted the following three indicators, expressed using Equations 6-8, to reflect the prediction error ($\Delta\delta$') intuitively:

1 RMSE

(δ)

i i n = = Δ $\sum$, (6)

Δ = $\sum$, (7)

oi i n =

Δ = − −

where RMSE is the root mean square error (‰); is the total number of samples; is the sample index (=1, 2, ···, denotes the isotope difference between the predicted stable isotope value and the observed stable isotope value for the sample (‰); MAPE is the mean absolute percentage error (%); δ represents the observed stable isotope value of the sample (‰); NSE

is the Nash-Sutcliffe efficiency (NSE=1 indicates perfect agreement between the predicted stable isotope value and the observed stable isotope value, whereas an NSE value close to 1 suggests high model reliability); and δ is the mean of the observed stable isotope values across all samples (‰). A positive NSE value implies that the model performs better than the mean of the observed stable isotope values, whereas a negative NSE value indicates poor model performance.

3 Results

3.1 Soil water content and soil particle size The data for the measured soil water content are shown in Figure 2

. Overall, for all five profiles, a consistent vertical trend of soil water content was observed: shallow layer<middle layer<deep layer. The mean soil water contents for the shallow, middle, and deep layers at each profile were as follows:

Figure 3

Figure 3: Figure 3

25.90%, 40.00%, and 43.80% at the Alaer profile, respectively; 13.20%, 22.60%, and 29.50% at the Ermuchang profile, respectively; 31.40%, 38.70%, and 45.00% at the Yingbazha profile, respectively; 4.80%, 21.40%, and 28.80% at the Aqike profile, respectively; and 11.00%, 37.70%, and 33.60% at the Yingsu profile, respectively. Shallow soil water was primarily impacted by surface evaporation, resulting in lower and more variable water contents. In contrast, the middle and deep soil layers at the Alaer and Yingbazha profiles presented relatively small fluctuations and adequate continuity in terms of soil water content. Conversely, intermittent low-moisture layers were observed in the middle and deep layers at the Ermuchang, Aqike, and Yingsu profiles, suggesting possible interruptions in hydraulic connectivity, which may also explain why the soil water content in the deep layer was lower than that in the middle layer at the Yingsu profile.

The analysis results for soil particle size are presented in Figure 3

. Overall, the soils were predominantly composed of silt and sand, with extremely low clay contents and considerable variation between adjacent layers. Soil particle size is the most critical factor impacting capillary rise height. At the Ermuchang and Aqike profiles, the deep soils were mainly sand-dominated, with an average sand fraction exceeding 95.00%.

Soil water content distribution across five soil profiles. (a), Alaer; (b), Ermuchang; (c), Yingbazha; (d), Aqike; (e), Yingsu.

Soil texture distribution across five profiles. (a), Alaer; (b), Ermuchang; (c), Yingbazha; (d), Aqike; (e), Yingsu. 3.2 Dual isotopes of precipitation, groundwater, surface water, soil water, and plant xylem water The stable isotope compositions of precipitation, groundwater, surface water, soil water, and plant xylem water differed significantly (Fig. 4 [FIGURE:4]). For groundwater, δ O and δD values ranged from -10.35‰ to -4.06‰ and from -70.85‰ to -38.52‰, respectively. For surface water, δ O and δD values ranged from -8.29‰ to -2.74‰ and from-51.30‰ to -30.34‰, respectively. Soil water exhibited a regression relationship of =3.47 -34.93 (where is the oxygen isotope ratio O) of soil water and is the deuterium isotope ratio (δD) of soil water; =0.92), with δ values ranging from -13.54‰ to 8.09‰ and δD values ranging from -88.31‰ to -13.51‰.

Shallow soil water was strongly affected by evaporation and exhibited high isotopic fluctuations, whereas the middle and deep soil layers remained relatively stable, with minimal variation. The O and δD values of plant xylem water ranged from -14.3‰ to -8.6‰ and from -91.1‰ to -67.9‰, respectively. The local meteoric water line (LMWL) in this zone was referenced from Song et al. (2022) as follows: =6.19 -4.79 (=0.92). Both the slope and intercept of the LMWL were lower than those of the global meteoric water line (=8.00 +10.00).

3.3 Different deuterium isotope corrections in xylem water for the predictions of plant water sources A comparative analysis of the isotope composition of plant xylem water and potential soil water sources at different depths (Fig. 5 [FIGURE:5]) revealed that the δD values of plant xylem water were generally lower than those of soil water, as most δD values of plant xylem water fell to the left of the soil water δD values. At the Ermuchang and Aqike profiles, in particular, the δD values of soil water at all depths exceeded those of plant xylem water, which directly highlights the necessity of accounting for deuterium depletion in xylem water when estimating plant water sources.

The Bayesian MixSIAR outputs (Fig. 6 [FIGURE:6]) further demonstrated that incorporating varying degrees of deuterium depletion in plant xylem water significantly influenced source attribution.

Moreover, the hydrological and geological conditions at each profile, as well as the plant species and size (including DBH and tree height), also exerted notable effects on the model predictions. 3.4 Statistical indicators under different deuterium correction models The average RMSE, MAPE, and NSE values of δD, calculated by comparing the predicted and observed values under the different levels of deuterium depletion for all P. euphratica

Relationship between oxygen isotope ratio (δ O) and deuterium isotope ratio (δD) of different water sources. The local meteoric water line (LMWL) (Song et al., 2022) and global meteoric water line (GMWL) are shown for reference. ramosissima samples, are presented in Table 2 . The results indicated that accounting for deuterium depletion significantly improves the estimation accuracy of plant water sources, as reflected by substantial improvements in all three statistical indicators estimated for δD. Under the F9 correction scenario, the RMSE of δD for P. euphratica decreased from 10.34‰ to 3.05‰, the NSE increased from -3.65 to 0.60, and the MAPE declined from 12.25% to 3.84%, representing a 68.65% reduction in relative error compared with the F0 scenario. Similarly, under the F11 correction scenario, the RMSE of δD for T. ramosissima decreased from 14.30‰ to 6.29‰, the NSE improved from -4.09 to 0.02, and the MAPE dropped from 15.43% to 4.98%, representing a 67.73% reduction in relative error compared with the F0 scenario.

In addition, we calculated the RMSE, MAPE, and NSE values for each of the five sampling profiles, as well as for groups P2, P3, T2, and T3. Groups P1, P4, T1, and T4 were excluded from this analysis due to their limited sample sizes and relatively greater uncertainty. The detailed results for these metrics are presented in Figure 7 [FIGURE:7].

The results revealed that the Alaer profile achieved the most optimal prediction accuracy under the F5 correction scenario, with the RMSE decreasing from 4.01‰ to 1.82‰, the NSE increasing from -2.62 to 0.25, and the MAPE decreasing from 4.70% to 2.20%. The best performances for Ermuchang and Yingbazha profiles were observed under the F11 correction scenario, where the RMSE decreased from 11.92‰ and 9.48‰ to 1.35‰ and 1.25‰, respectively;

the NSE improved from -57.68 and -22.07 to 0.25 and 0.60, respectively; and the MAPE decreased from 14.30% and 11.30% to 1.10% and 1.60%, respectively. For Aqike and Yingsu profiles, we observed the optimal performances under the F13 correction scenario, with the RMSE decreasing from 13.01‰ and 17.62‰ to 1.30‰ and 7.17‰, respectively; the NSE improving from -78.35 and -8.49 to 0.21 and -0.57, respectively; and the MAPE decreasing from 18.10% and 19.90% to 1.80% and 5.10%, respectively.

Among the plant groups, P2, T2, and T3 exhibited the most optimal predictive accuracies under the F11 correction scenario, with the RMSE decreasing from 11.01‰, 10.11‰, and 11.77‰ to 1.61‰, 2.06‰, and 3.17‰, respectively; the NSE improving from -8.85, -3.30, and -4.53 to 0.79, 0.82, and 0.60, respectively; and the MAPE decreasing from 14.10%, 12.50%, and 13.20% to 2.10%, 2.30%, and 3.70%, respectively. The P3 group performed best under the F9 correction scenario, with the RMSE decreasing from 9.26‰ to 2.36‰, the NSE increasing from -4.01 to 0.67, and the MAPE decreasing from 11.40% to 3.20%.

O and δD values of soil water and plant xylem water at different profiles. Panels (a), (b), (c), (d), and (e) correspond to the Alaer, Ermuchang, Yingbazha, Aqike, and Yingsu profiles, respectively. Panels a O, while panels a display δD. P1-P4 represent four groups of P. euphratica individuals based on diameter at breast height (DBH): <50, 50-10, 100-250, and >250 cm, respectively. T1-T4 represent four groups of ramosissima individuals based on plant height: <1.0, 1.0-2.0, 2.0-4.0, and >4.0 m, respectively. The asterisk symbol ' ' *' ' denotes different individual plants within the same group. Error bars represent standard deviations.

Bayesian Mixing Model for Stable Isotope Analysis in R (MixSIAR) predictions of plant water sources at the Alaer (a), Ermuchang (b), Yingbazha (c), Aqike (d), and Yingsu (e) profiles under different correction scenarios. F0, original δD and δ O values; F5, δD and δ O values were adjusted for -5.00‰ deuterium depletion; F7, δD and δ O values were adjusted for -7.00‰ deuterium depletion; F9, δD and δ O values were adjusted for -9.00‰ deuterium depletion; F11, δD and δ O values were adjusted for -11.00‰ deuterium depletion; F13, δD and δ O values were adjusted for -13.00‰ deuterium depletion. Error bars represent standard deviations.

RMSE, NSE, and MAPE of δD from the MixSIAR predictions under different correction scenarios Populus euphratica Tamarix ramosissima Note: RMSE, root mean square error; NSE, Nash-Sutcliffe efficiency; MAPE, mean absolute percentage error; δD, deuterium isotope ratio; MixSIAR, Bayesian Mixing Model for Stable Isotope Analysis in R. F0, original δD and δ O values; F5, δD and δ O values were adjusted for -5.00‰ deuterium depletion; F7, δD and δ O values were adjusted for -7.00‰ deuterium depletion; F9, δD and δ values were adjusted for -9.00‰ deuterium depletion; F11, δD and δ O values were adjusted for -11.00‰ deuterium depletion; F13, δD and δ O values were adjusted for -13.00‰ deuterium depletion.

4.1 Relationship between δD and δ

O among different water sources Water cycle processes govern the distinct δD and δ O isotopic signatures of various water bodies in arid zones. Owing to extremely low precipitation in arid zones, local rainfall contributes minimally to groundwater and soil water recharge and can be considered negligible (Herczeg and Leaney, 2011). Barbeta et al. (2019) also emphasized that trees are more likely to utilize soil water rather than direct rainfall as their primary water source—a pattern particularly relevant in arid environments. Consequently, soil water can be regarded as a mixture of groundwater and surface water inputs (Gao et al., 2023). As shown in Figure 4, the groundwater line was more closely aligned with the soil water line and plant xylem water distribution than with the surface water distribution, suggesting that groundwater is a more dominant contributor to both soil and plant xylem water than surface water. Soil water exhibited a wider range of isotopic variation, whereas plant xylem water showed a relatively narrower variation, primarily because shallow soil water is strongly impacted by evaporation, leading to significant isotopic enrichment (Zhu et al., 2022). Since plant xylem water is directly sourced from soil water and groundwater—and assuming no isotopic fractionation occurs during root water uptake—the dual-isotope values of plant xylem water should theoretically lie between those of the soil water line and groundwater line. However, the observed data revealed that, at similar δ O values, the δD values of plant xylem water are generally lower than those of soil water and groundwater, suggesting that isotopic alteration occurs between plant water and soil water, which is likely dominated by hydrogen isotope depletion, possibly induced by CVE during plant xylem water sample processing (Chen et al., 2020; Wen et al., 2023). 4.2 Impact of deuterium depletion on plant water sources Based on Bayesian MixSIAR predictions under different correction scenarios (Fig. 6), we found that introducing slight deuterium depletion led to an increased proportion of shallow water use and a decreased proportion of deep soil water use—consistent with the conclusions of Barbeta et al. (2019) and Cai et al. (2024), who reported that neglecting deuterium depletion in the estimation of plant water sources tends to overestimate the use of deep-water sources. As the degree of deuterium depletion correction increases, the proportion of shallow water use begins to decrease again, whereas the proportion of deep-water use rises once more. This finding indicates that although correcting for deuterium depletion in the estimation of plant water sources is essential (von Freyberg et al., 2020; Zhao et al., 2024), such correction should be applied within an optimal range.

We identified the optimal correction range for deuterium depletion by synthesizing the results of the three statistical metrics for deuterium isotopes (Table 2). The preliminary conclusion was that the most appropriate correction scenario for P. euphratica was F9, corresponding to a

Heatmaps of three statistical metrics—RMSE (root mean square error), NSE (Nash-Sutcliffe efficiency), and MAPE (mean absolute percentage error)—evaluated under different δD correction scenarios across soil profiles and plant groups.

(a), RMSE differentiated by soil profile; (b), RMSE differentiated by plant group; (c), NSE differentiated by soil profile; (d), NSE differentiated by plant group; (e), MAPE differentiated by soil profile; (f), MAPE differentiated by plant group. deuterium depletion of -9.00‰, whereas for T. ramosissima , it was F11 (deuterium depletion of -11.00‰). These values fell within the range proposed by Cai et al. (2024), suggesting that the deuterium depletion range of P. euphratica T. ramosissima is comparable to that of Lycium barbarum . As shown in Figure 7, deuterium depletion in plant xylem water tended to be greater in profiles located closer to the river, likely due to differences in soil water content and plant water sources. Specifically, soil water near the river was more strongly impacted by lateral recharge from the river, resulting in higher soil moisture (Fig. 2), which in turn increased the plant water content. This finding is consistent with that of Chen et al. (2020), who reported a positive correlation between deuterium depletion caused by CVE and plant water content. Regarding plant

groups (Fig. 7), for P. euphratica , the deuterium depletion estimated for group P2 was -11.00‰, lower than that of group P3 (deuterium depletion of -9.00‰), indicating that smaller euphratica individuals may have lower water content than larger ones. In contrast, for ramosissima , T2 and T3 presented similar deuterium depletion values of -11.00‰, suggesting relatively minor differences in water content across size classes. However, as the predefined range of deuterium depletion in this study was derived from research on other species, the actual extraction bias of P. euphratica T. ramosissima may extend beyond this interval. To obtain species-specific CVE bias more accurately, future studies should conduct controlled experiments using water with known isotope composition, thereby providing a more robust physical basis for such corrections. 4.3 Effects of water availability and vegetation traits on the utilization of plant water sources According to Bayesian MixSIAR-based results, regardless of whether deuterium depletion was considered, plants of varying sizes across all profiles consistently preferred to utilize deep soil water and groundwater rather than shallow or mid-depth soil water. This finding aligns with those of previous studies (Ehleringer et al., 1991; Cui et al., 2021; Cai et al., 2024), supporting the notion that plants in arid zones adopt distinctive water-use strategies by developing deeper root systems to access deep water sources (Fan et al., 2017). For further discussion, we used the optimal correction scenarios identified in the above section: F9 for P. euphratica and F11 for ramosissima Regarding profile locations, the differences in upstream–downstream position and distance from the river channel result in variations in the average proportions of water sources used by plants. In general, plants located farther downstream and at greater distances from the river tend to rely more on deep soil water and groundwater, which may be attributed to the diminished lateral recharge from surface water with increasing distance from the river, rendering shallow and mid-depth soil water insufficient to sustain plant growth and forcing plants to depend on deep water sources. Field data revealed that among the three profiles closer to the river, Alaer and Yingbazha exhibited higher and more continuous soil water content, whereas Ermuchang presented lower soil moisture and possible hydraulic disconnection (Fig. 2), partially supporting this inference. However, the representativeness of single-time soil moisture data may be limited because of the lack of temporal continuity in our sampling and the well-documented time lag between plant water use and soil moisture variation (Sloan et al., 2021). Moreover, several studies have suggested that root distribution may play a more decisive role than soil water content in determining the depth of plant water uptake (Gardner, 1964; Soylu et al., 2017; Cai et al., 2022).

Prolonged drought can alter root architecture in arid environments, driving plants to develop deeper roots to access deep soil water and groundwater (Horton et al., 2001b; Zeng et al., 2019).

Consequently, deeper roots may proliferate while shallower roots would die under water stress conditions (Fu et al., 2014; Maihemuti et al., 2021), causing plants to remain dependent on deep water sources even during the periods of increased surface soil moisture.

With respect to plant species, the differences in water use proportions from various soil layers between P. euphratica T. ramosissima were minimal. Both species exhibited extremely low utilization of shallow soil water and moderate use of mid-depth soil water, while the combined utilization of deep soil water and groundwater accounted for 61.45% for P. euphratica 59.95% for T. ramosissima . This finding differs from those of previous studies (Li et al., 2017; Li et al., 2022; Wan et al., 2022), which suggested that T. ramosissima accesses deeper soil water or groundwater more effectively than P. euphratica . Wang et al. (2023) reported that the root depth T. ramosissima can reach up to 7.5 m in some extremely arid zones, far exceeding the expected depth of 3.0 m. Chen et al. (2016) noted that at groundwater depths less than 3.8 m, P. euphratica T. ramosissima exhibit potential competition for water resources, whereas at the depth of 7.2 m, this competitive relationship diminishes significantly. A possible explanation of this difference is that the groundwater depths in the studied profiles are relatively shallow (within 3.0 m),

accessible to both ramosissima P. euphratica . Therefore, a groundwater depth of 3.0 m does not sufficiently distinguish their capacities to utilize deep water sources.

In terms of plant size, except for P4, both P. euphratica T. ramosissima generally tended to rely more on deep soil water and groundwater. This finding contrasts with the conclusions of Liu et al. (2015) and may be attributed to interspecific competition. Considering the relatively shallow groundwater table at our study profiles (<3.0 m), the roots of most plants can reach or approach the groundwater. Su et al. (2022) reported that T. ramosissima primarily utilizes soil water when it is readily available, switching to groundwater only under conditions of soil water depletion. This preference is attributed to the lower energy cost associated with extracting soil water—a more favorable water source compared to groundwater (Holland et al., 2006). Therefore, in shallow and middle soil layers where moisture is relatively low, larger-sized plants—owing to greater water uptake capacity—may outcompete smaller individuals for limited soil water. Consequently, smaller-sized plants may be forced to rely more heavily on deep soil water and groundwater. The lower proportion of groundwater use by plants in P4 compared to P3 may be related to physiological constraints, hydraulic limitations, or sampling uncertainty. This result is preliminary and should be interpreted cautiously.

Notably, our sampling was conducted only once, in mid-July 2022, representing a single temporal snapshot. Plant water-use strategies may vary seasonally and interannually in response to changes in water availability and environmental conditions. Therefore, the correction values and patterns identified here require validation across different seasons, years, and broader spatial scales. In addition, the relatively small and unevenly distributed sample size may have introduced uncertainties and limited the robustness of intergroup inferences. Future research should employ a sampling design with larger sample sizes that are both temporally continuous and more evenly distributed across space to reduce such uncertainties.

5 Conclusions

In this study, we employed stable isotope analysis to investigate the water sources of euphratica T. ramosissima along the mainstream of the Tarim River and quantified CVE-induced deuterium depletion using the Bayesian MixSIAR model. The results indicated that the optimal deuterium correction values are -9.00‰ for P. euphratica and -11.00‰ for ramosissima . Both species primarily relied on deep soil water and groundwater, with a stronger dependence observed in small-sized individuals and those growing farther from the river. Plants closer to the river exhibited greater deuterium depletion in plant xylem water, suggesting higher water content and stronger connectivity with shallow riparian moisture. Despite variations in habitat and plant size, the two species exhibited similar vertical water-use patterns, likely due to the relatively shallow groundwater table.

The main uncertainties arise from the limited number of samples and the lack of temporal continuity in sampling. Future studies should incorporate high-frequency sampling and molecular-level analyses to improve the accuracy of plant water source identification. Overall, the findings of this study clarify the magnitude of CVE bias and provide valuable insights for understanding plant water-use strategies and supporting water resource management in arid environments.

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figure 10

Figure 4: Figure 10

Figure 13

Figure 5: Figure 13

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Figures

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Figure 31

Figure 6: Figure 31

Figure 38

Figure 7: Figure 38