Postprint: Water Sources of Populus euphratica Under Varying Groundwater Depths in the Lower Tarim River

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Abstract

Groundwater and soil water are the determining factors for desert vegetation growth in arid regions, and water utilization by desert vegetation constitutes a critical component of eco-hydrological processes in these areas. To better understand water utilization by desert vegetation, we employed hydrogen and oxygen stable isotope technology combined with the Bayesian mixing model (MixSIAR) to analyze water uptake sources of Populus euphratica trees of different stand ages under varying groundwater depths. The results show that: (1) The $ $18O and δD values of soil water decrease with increasing soil depth and increase with increasing distance from the river; the $ $18O and δD values of xylem water in middle-aged Populus euphratica exhibit the greatest variation, followed by old-aged trees, with young trees showing the least variation; the $ $18O and δD values of groundwater decrease with increasing distance from the river. (2) For Populus euphratica trees of different ages under varying groundwater depths, the primary water uptake layer is groundwater, followed by deep soil water, and trees near the riverbank can directly utilize river water. When groundwater depths are 1.98~2.10 m, 1.95~2.21 m, 2.49~2.61 m, 3.51~3.73 m, and 4.66~4.73 m, the utilization proportions of groundwater by old-aged Populus euphratica are 18.4%, 19.6%, 17.8%, 23.1%, and 21.9%, respectively; those by middle-aged trees are 16.7%, 17.6%, 16.7%, 21.4%, and 21.6%; and those by young trees are 16.0%, 16.6%, and 19.9% (no seedlings were present in plots with depths of 2.49~2.61 m and 4.66~4.73 m). (3) Groundwater depth increases with increasing distance from the river; soil water content and soil salinity decrease with increasing distance from the river and increase with increasing soil depth; the utilization proportion of water sources by Populus euphratica increases with increasing soil water content and salinity. Investigating the water uptake sources of Populus euphratica under different groundwater depths provides theoretical support for the ecological restoration of desert riparian forests in the lower

reaches of the Tarim River.

Full Text

Water Utilization Sources of *Populus euphratica* Under Different Groundwater Depths in the Lower Reaches of the Tarim River

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Abstract

Groundwater and soil water are critical determinants of desert vegetation growth in arid regions, and water utilization by desert vegetation constitutes an essential component of ecohydrological processes in these areas. To better understand water utilization patterns of desert vegetation, this study employed hydrogen and oxygen stable isotope techniques combined with the Bayesian mixing model (MixSIAR) to analyze water absorption sources of *Populus euphratica* across different forest ages under varying groundwater depths. The results revealed that: (1) Soil water δ^{18}O and δD values decreased with increasing soil depth and increased with greater distance from the riverbank; xylem water δ^{18}O and δD values exhibited the highest variability in middle-aged trees, followed by old and young trees; groundwater δ^{18}O and δD values decreased with increasing distance from the riverbank. (2) The primary water source for *Populus euphratica* across different forest ages and groundwater depths was groundwater, followed by deep soil water; trees near the riverbank could directly utilize river water. (3) Groundwater depth increased with distance from the riverbank, whereas soil water content and salinity decreased with distance from the riverbank but increased with soil depth; the proportion of water source utilization by *Populus euphratica* increased with soil water content and salinity. Investigating water utilization sources of *Populus euphratica* under different groundwater depths provides theoretical support for ecological restoration of desert riparian forests in the lower Tarim River.

Key words: hydrogen and oxygen stable isotopes; MixSIAR model; water source; groundwater burial depth; *Populus euphratica*; lower Tarim River

1 Introduction

Water is a crucial driver of plant growth and distribution, particularly in desert regions where soil water and groundwater play decisive roles in vegetation development. Under the influences of global climate warming and increasingly frequent agricultural irrigation, evaporation rates of surface water accelerate and groundwater levels decline in arid zones, gradually shifting plant water utilization sources toward deeper soil water or groundwater. Therefore, investigating plant water utilization sources in arid regions enhances understanding of ecohydrological processes and provides important practical significance for water resource management in these areas.

Currently, traditional methods for partitioning plant water sources include complete root excavation, sap flow measurement, and plant water potential techniques. Although these methods are relatively convenient to implement, they have limitations. Complete root excavation is time-consuming, labor-intensive, and causes severe damage to vegetation; sap flow techniques and plant water potential methods rely on instantaneous plant physiological indicators and cannot accurately calculate the contribution rates of potential water sources. Stable isotope technology is considered an efficient research tool because isotopes generally do not fractionate during plant water uptake, enabling precise determination of plant water sources by comparing isotopic compositions of xylem water with potential sources.

Hydrogen and oxygen stable isotope techniques combined with isotopic mixing models have been widely applied to estimate water sources of desert vegetation in arid regions. Existing research has revealed that water sources of desert vegetation exhibit variability across seasonal changes, different growth periods, and among different tree species. Regarding seasonal variations, Li Ronglei et al. [citation] demonstrated that *Salix psammophila* primarily utilized deep soil water and groundwater during the dry season, gradually shifting to shallow soil water absorption during the rainy season. Another study using stable isotope techniques concluded that *Nitraria tangutorum* shrubs increased their utilization proportion of deep soil water and precipitation during the water transport period. Zhao Peng et al. [citation] indicated that *Tamarix ramosissima* at different decline stages exhibited higher average utilization proportions of precipitation in spring, with declining shrubs tending to utilize reliable deep groundwater from spring to autumn.

Regarding variations across different growth periods, [citation] found that mature and over-mature *Populus euphratica* in the lower Heihe River utilized deep soil water at higher proportions. Li Tao et al. [citation] employed the IsoSource model to determine that the utilization proportion of river water by *Populus euphratica* at different growth stages increased with diameter class. Wan Yanbo et al. [citation] using the IsoSource model revealed that young *Populus euphratica* primarily absorbed water from shallow soil layers, while mature and over-mature trees were less affected by groundwater depth in their water absorption layers.

Among different tree species, Wang Yuyang et al. [citation] using stable isotope technology discovered that *Populus euphratica* and *Tamarix ramosissima* utilized deep soil water and groundwater at relatively large proportions, whereas *Glycyrrhiza uralensis* and *Alhagi sparsifolia* primarily used shallow soil water.

Populus euphratica is the dominant constructive species in the lower reaches of the Tarim River, playing a vital role in oasis protection and safeguarding human production and livelihood. Since the implementation of the national ecological water conveyance project in 2000, the downstream *Populus euphratica* ecological environment has gradually recovered, but the communities remain in a state of decline and degradation, with only a small number of young trees surviving near riverbanks. Therefore, this study applied stable isotope tracing and the MixSIAR model to quantify the contribution proportions of various potential water sources to *Populus euphratica*, aiming to: (1) analyze the hydrogen and oxygen stable isotope composition characteristics of potential water sources; (2) investigate the main water absorption layers and utilization proportions of different-aged *Populus euphratica* under varying groundwater depths; and (3) examine how soil physicochemical properties and groundwater depth influence water utilization sources, thereby providing scientific guidance for ecological restoration and management of *Populus euphratica* forests of different ages in the lower Tarim River.

1.1 Study Area Overview

The study area was located at the Kunast section (87°50 56.40 E, 40°21 39.60 N) and Yingsu section (88°03 36.00 E, 40°24 25.20 N) in the lower reaches of the Tarim River [Figure 1: see original paper]. The region experiences a typical warm temperate continental arid climate, with average annual precipitation less than 15 mm, potential annual evaporation reaching 2500–3000 mm, and average annual temperature of 9–11°C. The plant community is primarily composed of *Populus euphratica*, *Tamarix ramosissima*, *Haloxylon ammodendron*, *Nitraria tangutorum*, *Glycyrrhiza uralensis*, *Karelinia caspia*, and other species. *Populus euphratica* communities are distributed along both riverbanks, but only middle-aged and old trees survive in communities far from the riverbank.

1.2 Sample Collection and Processing

On June 15-16, 2023, sampling plots were established at distances of 0–5 m, 200–210 m, 400–410 m, and 800–810 m from the river within the Kunast and Yingsu sections, based on groundwater monitoring well distribution, totaling six plots. The Kunast section Plot II was an experimental field for *Populus euphratica* seedlings with periodic groundwater irrigation, where salt crusts were present [Figure 2: see original paper]. The Yingsu section Plot III contained large areas of *Populus euphratica* seedlings [Figure 3: see original paper]. Young, middle-aged, and old trees were selected in each plot, totaling 18 sample trees (6 per age class). Basic information on sample trees is provided in .

1.2.1 Soil Sample Collection Beneath selected sample trees, soil samples were collected using a soil auger (diameter 5 cm) at 20 cm intervals from the surface, with 10 samples per layer. For riverbank plots, sampling extended to the water table (0–200 cm), yielding 18 soil sample groups. One portion was sealed in sample bottles with Parafilm and stored at -20°C for soil water extraction and stable isotope analysis. Another portion was placed in aluminum boxes, sealed, and weighed immediately to determine fresh weight, then brought to the laboratory for soil water content and salinity measurement.

1.2.2 Plant Sample Collection To avoid evaporation effects, sampling was conducted between 8:00–10:00 AM. Non-green, lignified twigs without pests, diseases, or human disturbance were cut with pruning shears. Bark was quickly removed, and samples were placed in bottles, sealed with Parafilm, and brought to the laboratory immediately for water extraction and stable isotope analysis, yielding 18 plant samples.

1.2.3 Groundwater and River Water Sample Collection Groundwater samples were collected from monitoring wells near the plots (6 samples). River water was collected from the river adjacent to the plots (2 samples). Sample bottles were rinsed three times with the water being collected before filling. Bottles were sealed with Parafilm, and in the laboratory, water was filtered through 0.45 m cellulose acetate membranes and stored in 1.5 mL vials at 4°C until stable isotope analysis.

1.3 Analytical Methods

1.3.1 Water Extraction and Stable Isotope Composition Determination Water extraction and hydrogen-oxygen stable isotope composition determination were completed at the Xinjiang Laboratory of Lake Environment and Resources in Arid Zone, Xinjiang Normal University. All water samples were extracted using an automatic vacuum condensation extraction system (LGR DLI-210, Beijing LICA United Technology Ltd.). Hydrogen and oxygen stable isotope compositions were measured using a liquid water stable isotope analyzer (Los Gatos Research, Mountain View). To improve measurement accuracy of plant water δ^2H values, organic matter correction curves were applied to plant water isotopic compositions, ensuring organic matter effects remained within acceptable error ranges. Isotope compositions were expressed as per mil deviations (‰) from Vienna Standard Mean Ocean Water (VSMOW):

$$\delta(‰) = (R_{sample} - R_{standard}) / R_{standard} \times 1000$$

where R_{sample} and $R_{standard}$ represent the isotope ratios of the sample and standard, respectively. Measurement precision was $\pm$0.5‰ for δ^2H and $\pm$0.1‰ for δ^{18}O.

1.3.2 MixSIAR Model and Uncertainty Analysis The Bayesian mixing model MixSIAR, an R package, was used to quantitatively determine the contribution rates of potential water sources to plant water. Before accepting final model outputs, convergence diagnostics were performed. When the Gelman-Rubin diagnostic showed <5% of parameters outside the 1.96 range and Geweke diagnostics indicated convergence, the model was considered converged. Model performance was evaluated using root mean square error (RMSE):

$$\mathrm{RMSE} = \sqrt{[\Sigma(p\_i - o\_i)^2 / n]}$$

where p_i represents the predicted isotope ratio of plant xylem water, o_i is the observed value, and n is the number of plant water sources. Lower RMSE values indicate better model applicability.

1.3.3 Soil Water Content and Salinity Measurement Soil water content was determined using the oven-drying method at 105°C to constant weight. Soil salinity was measured using a conductivity meter (Multi 3420 Set B, WTW GmbH, Germany).

2 Results

2.1 Groundwater Depth and Soil Physicochemical Properties

Groundwater depth increased with distance from the riverbank. In the Kunast section, monitoring well depths increased from 2.78 m to 3.08 m; in the Yingsu section, from 1.95 m to 4.73 m [Figure 4: see original paper]. Soil water content decreased with distance from the riverbank but increased with soil depth [Figure 5: see original paper]. In the Kunast section, average soil water content in the 0-40 cm, 40-120 cm, and 120-200 cm layers was 2.90%, 11.04%, and 16.62%, respectively, in Plot I; 1.56%, 4.13%, and 20.56% in Plot II; and 0.20%, 1.71%, and 24.78% in Plot III. In the Yingsu section, corresponding values were 3.06%, 4.52%, and 16.62% in Plot I; 1.59%, 12.88%, and 20.56% in Plot II; and 0.14%, 0.92%, and 24.78% in Plot III.

Soil salinity was high throughout the study area, decreasing with distance from the riverbank and increasing with soil depth [Figure 6: see original paper]. In the Kunast section, electrical conductivity (EC) in the 0-40 cm layer was 754.33, 509.67, and 249.25 $\mathrm{S \cdot cm^{-1}}$ in Plots I, II, and III, respectively. In the Yingsu section, EC values were 894.50, 731.00, and 1393.25 $\mathrm{S \cdot cm^{-1}}$.

2.2 Soil Water Stable Isotope Composition

Soil water δ^{18}O and δD values decreased with increasing soil depth [Figure 7: see original paper]. In the Kunast section, δ^{18}O values ranged from -5.79‰ to -9.23‰, with minimum values in the 0-40 cm layer of middle-aged trees in Plot I and the 160-200 cm layer of old trees in Plot III. Maximum values occurred in the 80-120 cm layer of middle-aged trees in Plot I. Variation amplitude in δ^{18}O values was 4.44‰ in Plot I, 3.51‰ in Plot II, and 2.90‰ in Plot III. In the Yingsu section, δ^{18}O values ranged from -6.87‰ to -9.00‰, with variation amplitudes of 2.13‰, 1.98‰, and 1.95‰ in Plots I, II, and III, respectively.

2.3 Xylem Water Stable Isotope Composition

Xylem water δ^{18}O and δD values varied with tree age and plot location [Figure 8: see original paper]. In the Kunast section, δ^{18}O values ranged from -5.79‰ to -9.23‰, with maximum values in old and middle-aged trees in Plot III and minimum values in middle-aged trees in Plot II. In the Yingsu section, δ^{18}O values ranged from -8.87‰ to -16.5‰, with maximum values in middle-aged trees in Plots I and III and minimum values in young trees in Plot II.

Variability was highest in middle-aged trees, followed by old and young trees. In the Kunast section, variation amplitudes were 3.44‰ for young trees, 3.51‰ for middle-aged trees, and 3.49‰ for old trees. In the Yingsu section, amplitudes were 2.98‰, 7.63‰, and 2.13‰, respectively.

2.4 Groundwater Stable Isotope Composition

Groundwater δ^{18}O and δD values became more depleted with increasing distance from the riverbank [Figure 9: see original paper]. In the Kunast section, groundwater δ^{18}O values ranged from -8.87‰ to -9.23‰, with a variation amplitude of 0.36‰. In the Yingsu section, values ranged from -9.00‰ to -9.23‰, with a variation amplitude of 0.23‰. Groundwater δD values also decreased with distance from the riverbank.

2.5 Water Sources and Utilization Proportions

Water source contributions varied significantly among tree ages and plots in both sections [FIGURE:10, FIGURE:11]. In the Kunast section: - **Plot I** (groundwater depth 1.95-2.21 m): Young trees primarily used groundwater (16.6%) and river water (16.9%). Middle-aged and old trees mainly used groundwater (19.9% and 21.4%) and river water (23.1% and 19.6%), with old trees showing the highest groundwater utilization. - **Plot II** (groundwater depth 3.51-3.73 m): All age classes primarily used groundwater (young: 16.7%, middle-aged: 21.4%, old: 23.1%). Young trees also used shallow soil water (0-40 cm), while middle-aged and old trees used river water. - **Plot III** (groundwater depth 4.66-4.73 m): Middle-aged and old trees primarily used groundwater (21.6% and 21.9%) and deep soil water (160-200 cm), with utilization proportions of 16.4% and 17.0%, respectively.

In the Yingsu section: - **Plot I** (groundwater depth 1.98-2.10 m): No young trees survived. Middle-aged and old trees primarily used groundwater (17.8% and 18.4%) and river water (16.7% and 15.2%). - **Plot II** (groundwater depth 2.49-2.61 m): Young trees primarily used groundwater (16.0%) and river water (14.9%). Middle-aged trees used river water most (18.4%), followed by groundwater (17.6%) and shallow soil water (16.4%). - **Plot III** (groundwater depth 4.66-4.73 m): Young trees primarily used groundwater (16.7%) and river water (14.4%). Middle-aged and old trees mainly used groundwater (18.3% and 18.2%) and deep soil water (15.8% and 13.9%).

3 Discussion

3.1 Response of Water Utilization Sources to Groundwater Depth Variations

Populus euphratica is a deep-rooted species with high dependence on groundwater. When groundwater depth is less than 4 m, trees can normally absorb water; when depths exceed 9 m, trees experience drought stress leading to decline and mortality. Maintaining appropriate groundwater depths is therefore crucial for ecological restoration of desert riparian forests.

This study found that young trees absorbed water from shallow soil layers, while middle-aged and old trees primarily utilized deep soil water and groundwater, consistent with previous research. Trees near riverbanks could directly use river water, with middle-aged trees showing the highest river water utilization proportion, followed by young trees and old trees.

When groundwater depth was 1.95–3.73 m, trees of all ages mainly used groundwater, river water, and shallow soil water. At greater depths (4.66–4.73 m), middle-aged and old trees primarily relied on groundwater and deep soil water. The absence of young trees in plots with deeper groundwater suggests that seedling establishment requires shallower groundwater conditions.

3.2 Influence of Soil Physicochemical Properties on Water Absorption

The lower Tarim River region is extremely arid. Surface soil isotopic enrichment was primarily caused by evaporation. When shallow soil water content (0–40 cm) was low, trees of all ages mainly used groundwater and deep soil water. *Populus euphratica* seedlings only survived on riverbanks with higher shallow soil water content, consistent with previous findings.

In addition to drought stress, salinity stress affected water uptake strategies. The average utilization proportion of shallow soil water (0–40 cm) by *Populus euphratica* decreased with increasing soil salinity. When soil EC was 509.67 $\mathrm{S \cdot cm^{-1}}$, shallow soil water utilization was 14.1%; at 754.33 $\mathrm{S \cdot cm^{-1}}$, it decreased to 12.3%. This indicates that *Populus euphratica* preferentially absorbs water from less saline sources (deep soil water, river water, groundwater) in high-salinity areas. However, at the lowest EC (249.25 $\mathrm{S \cdot cm^{-1}}$), shallow soil water utilization was only 7.6% due to extremely low water content (0.20%) and deep groundwater (4.66–4.73 m), demonstrating that soil water availability and groundwater depth also strongly influence water uptake strategies.

This study provides preliminary insights into water source partitioning by different-aged *Populus euphratica* in the lower Tarim River, clarifying how water uptake strategies respond to groundwater depth variations and providing a theoretical basis for ecological water conveyance and community restoration. Future research should further refine the gradients of distance from riverbank and groundwater depth for more comprehensive understanding.

4 Conclusion

1. Soil water δ^{18}O and δD values decreased with soil depth and increased with distance from the riverbank. Xylem water δ^{18}O and δD values showed the greatest variation in middle-aged trees, followed by old and young trees. Groundwater δ^{18}O and δD values decreased with distance from the riverbank.
2. Groundwater was the primary water source for *Populus euphratica* across all ages and groundwater depths, followed by deep soil water. River water could be directly utilized by trees near the riverbank. The proportion of groundwater utilization increased with distance from the riverbank, with old trees showing the highest utilization (18.4–21.9%), followed by middle-aged trees (16.7–21.6%) and young trees (16.0–19.9%).
3. Water utilization sources were closely related to groundwater depth and soil physicochemical properties. At groundwater depths of 1.95–3.73 m, trees mainly used groundwater, river water, and shallow soil water. At 4.66–4.73 m, middle-aged and old trees primarily used groundwater and deep soil water. Low soil water content, deep groundwater, and high soil salinity were unfavorable for *Populus euphratica* water uptake.

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Note: Figure translations are in progress. See original paper for figures.