

## Response of *Populus euphratica* Community Characteristics to Groundwater Level Gradient in Desert Riparian Forest (Postprint)

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### Abstract

Based on field survey data of *Populus euphratica* communities in the Tarim desert riparian forest and groundwater level monitoring data, multivariate statistical methods and Hill and diversity index measurement methods were applied to investigate the variation patterns and interrelationships of quantitative characteristics of the dominant *Populus euphratica* population along a groundwater level gradient, and to explore the ecological response of community species diversity to the groundwater level gradient. The results showed that hierarchical clustering method classified the *Populus euphratica* communities at different groundwater levels in the desert riparian forest into three groups. The diameter at breast height, crown width, coverage, density, and mortality rate of the dominant population showed extremely significant correlation with groundwater level ( $P < 0.01$ ). With decreasing groundwater level, the growth of the dominant species declined, the withering rate increased significantly, and the population degraded. Hill diversity exhibited three distinct change stages along the groundwater level gradient. When the groundwater level was 4-6 m, the diversity index sharply declined and the curve gradually flattened, indicating that species diversity began to be impaired. Both Cody ( $c$ ) and Whittaker ( $w$ ) indices increased with the groundwater level gradient, while the Sorensen ( $s$ ) index showed a decreasing trend.  $s$ ,  $c$ , and  $w$  were all extremely significantly correlated with groundwater level difference ( $P < 0.01$ ). When groundwater level  $> 4$  m,  $c$  and  $w$  values increased significantly while  $s$  values decreased significantly. Comprehensive analysis revealed that when groundwater level  $< 4$  m, the *Populus euphratica* community structure was similar with many shared species, the dominant species exhibited good growth, and this represented the suitable ecological water level for dominant population survival. When groundwater level  $> 4$  m, community species diversity and accompanying species decreased, the rate of species change increased, habitat heterogeneity increased, quantitative characteristics of the dominant population changed significantly,

and community structure was simplified. At approximately 6 m groundwater level, vegetation degraded, species diversity sharply declined, and the dominant species became sparse and declining. Therefore, the reasonable ecological groundwater level for vegetation restoration in the Tarim desert riparian forest should be maintained at approximately 4 m.

## Full Text

## Preamble

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## Response of *Populus euphratica* Communities in Desert Riparian Forests to Groundwater Level Gradients in the Tarim Basin

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## Abstract

Based on field survey data of *Populus euphratica* communities in the Tarim desert riparian forest and groundwater monitoring data, this study applied multivariate statistical analysis,  $\alpha$ -diversity index measurement, and Hill diversity index methods to investigate the ecological responses of community species diversity to groundwater level gradients. We examined the variation patterns of quantitative characteristics of the dominant *P. euphratica* population along groundwater level gradients and their interrelationships. Using systematic cluster analysis, desert riparian forest *P. euphratica* communities at different groundwater levels were classified into three distinct types. The quantitative characteristics of the *P. euphratica* population were significantly correlated with groundwater level gradients ( $P < 0.01$ ). As groundwater levels decreased, the growth vigor of the dominant species weakened, and population structure transitioned from expanding to declining. Species diversity varied considerably across the three plot types with decreasing groundwater levels. Specifically, when groundwater levels exceeded 4 m, species diversity began to decline. When groundwater levels ranged from 4–6 m, the Hill diversity index decreased sharply and the diversity curve became smooth. The diversity indices (Cody  $h'$ , Whittaker  $w$ , and Sorensen  $s$ ) showed significant correlations with groundwater level differences ( $P < 0.01$ ). The  $w$  value increased significantly while the  $s$  value decreased significantly as groundwater levels fell. At groundwater levels  $> 4$  m, the diameter at breast height (DBH) and mortality rate of the dominant population increased significantly. Species diversity decreased sharply with the

groundwater level gradient, showing two distinct change stages. At groundwater levels  $< 4$  m, the dominant species grew well, representing the suitable ecological water table for population survival. At groundwater levels  $> 4$  m, species diversity and associated species decreased rapidly, species turnover rate increased, habitat heterogeneity intensified, quantitative characteristics of the dominant population changed significantly, and community structure became simplified. When groundwater levels reached approximately 6 m, vegetation became degraded and the dominant population declined considerably. Therefore, the rational ecological groundwater level for restoring degraded desert vegetation in extremely arid areas should be maintained at about 4 m.

**Keywords:** desert riparian forest; *Populus euphratica* community; Hill diversity; -diversity; groundwater level gradient

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## 1. Study Area Overview

The upper reaches of the Tarim River extend from the confluence of the Aksu, Yarkant, and Hotan Rivers at Xiaoqiao to Yingbazha in Luntai County ( $40^{\circ}28' N$ ,  $80^{\circ}56' E$  to  $41^{\circ}10' N$ ,  $84^{\circ}36' E$ ), spanning 495 km. The region has a typical warm temperate continental arid climate with abundant light and heat resources. The total solar radiation is  $5,796 \text{ MJ/m}^2$ , annual sunshine duration is 2,729.0 hours, annual precipitation is 50.4 mm, annual evaporation is 2,011.4 mm, the continuous daily average temperature  $10^{\circ}\text{C}$  is 201 days, the extreme maximum temperature is  $39.4^{\circ}\text{C}$ , and the extreme minimum temperature is  $-25.0^{\circ}\text{C}$ . Summer winds are strong, and sandstorm disasters are frequent natural hazards. The plant community structure is simple with obvious three-layer structure of trees, shrubs, and grasses, and low species diversity. The dominant species is *Populus euphratica*, with common understory species including *Tamarix ramosissima*, *Halimodendron halodendron*, *Lycium ruthenicum*, *Alhagi sparsifolia*, *Phragmites australis*, and *Glycyrrhiza uralensis*. The soil type is forest meadow soil.

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## 2. Methods

### 2.1 Plant Community Survey and Groundwater Measurement

Based on field reconnaissance in the upper Tarim River desert riparian forest, we selected representative forest stands with minimal human disturbance. Study sections were established at Nankou Town in the upper segment (U1), Shayi in the middle segment (M1), and Lunnan Town in the lower segment (L1). Belt transects were set perpendicular to the riverbank at each section. According to vegetation growth status and groundwater levels, each transect was divided into 100 m intervals, establishing  $25 \text{ m} \times 25 \text{ m}$  plots using the adjacent grid method. In each plot, all trees and shrubs with DBH  $\geq 2.0$  cm were measured,

recording species name, DBH, height, and canopy diameter. Tree seedlings were counted by base plant units. Shrubs were measured at ground diameter. Canopy coverage was recorded. Herbaceous layers were surveyed using 1 m × 1 m quadrats along diagonal lines to record species and abundance. Longitude, latitude, elevation, and canopy density were recorded for each plot.

Soil moisture was measured using the drying method at 20 cm intervals along diagonal lines in each plot. Groundwater levels were monitored using PVC pipes (1.5 m, 10 m depth) for long-term observation. Soil water content was determined by the drying method, and electrical conductivity was measured by the conductometric method.

## 2.2 Population Structure Analysis

We applied size structure analysis from ecology to study population age structure characteristics. Although age class and diameter class differ for a species, they show consistent responses to environmental conditions. Following the Technical Regulations for Forest Resource Planning and Design Survey (2003) and considering the life history and habitat heterogeneity of *P. euphratica*, we divided the population into age classes: diameter class 0–2 cm, 2–4 cm, then 4 cm intervals thereafter, with diameters >40 cm counted as one class. The number of individuals in each age class and their percentage of the total were calculated to construct age structure diagrams. Canopy diameter was calculated as  $(d_{\text{east-west}} + d_{\text{north-south}})/2$ .

## 2.3 Diversity Indices

Parameter-containing diversity indices help reveal how environmental or spatiotemporal changes affect diversity and facilitate ecological interpretation. We introduced the Hill diversity index ( $H_p$ ,  $0 < p < 1$ ), where  $H_0$  gives species richness,  $H_1$  gives the Shannon-Weiner index,  $H_{1/e}$  gives the Brillouin index, and  $H_2$  gives the Simpson index.  $P_i$  represents the proportion of abundance of the  $i$ th species.

$\beta$ -diversity measures differences in species composition among habitats, revealing the degree of habitat partitioning along environmental gradients, habitat diversity, and species replacement rates. We used Sorensen ( $\beta_s$ ), Cody ( $\beta_c$ ), and Whittaker ( $\beta_w$ ) indices:  $\beta_s = 2c/(a+b)$ ,  $\beta_c = (a+b-2c)/2$ ,  $\beta_w = S/ma - 1$ , where  $S$  is total species number,  $ma$  is average species number,  $a$  and  $b$  are species numbers in two communities, and  $c$  is shared species number.

## 2.4 Statistical Analysis

Ward's method (sum of squared deviations) is an effective classification method widely used in ecological sciences. Based on species composition, population quantitative indicators, and groundwater level data from 45 plots in the upper Tarim River, we performed cluster analysis using Ward's method. Regression

analysis was conducted between *P. euphratica* population quantitative indicators and groundwater levels in different habitats. First-order derivatives of fitted curves were calculated to determine suitable survival water levels and groundwater thresholds. SPSS 19.0 and Origin 8.0 software were used for data analysis.

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### 3. Results

#### 3.1 Response of *Populus euphratica* Community Characteristics to Groundwater Level Gradients

The dominant population serves as a reliable indicator of environmental gradients, and its dynamic changes are visible signs of ecological change. Based on cluster analysis, three habitat types were identified:

**H1 (Groundwater level < 2 m):** Located near river channels (<200 m) with frequent flooding. The dominant species were *P. euphratica* and *Halimodendron halodendron*. Community species composition was diverse, with shallow-rooted mesophytic herbs as associated species. Seeds of dominant and associated species germinated on floodplains with adequate soil moisture, forming young forests with high species diversity and density.

**H2 (Groundwater level 2-4 m):** As distance from the river increased and groundwater levels declined, soil moisture decreased. Some shallow-rooted and mesophytic herbs gradually disappeared. Communities were mainly composed of *P. euphratica* and *Alhagi sparsifolia*. The herb layer was distinct, but surface flooding supply was lost. Vegetation primarily relied on shallow groundwater. *P. euphratica* seeds could not germinate due to insufficient moisture, lacking regeneration and failing to meet seedling growth requirements, forming a pattern of young and mature forests coexisting.

**H3 (Groundwater level 4-6 m):** At greater distances from the river, some mesophytic and drought-intolerant shrubs and perennial deep-rooted herbs could not adapt to the increasingly arid environment and exited the community. Small-diameter dominant species could not absorb groundwater and died standing. Only deep-rooted, drought-resistant *P. euphratica* and *Tamarix ramosissima* remained, forming over-mature forests with simple community structure and low species diversity.

#### 3.2 Response of *Populus euphratica* Population Structure to Groundwater Level Gradients

Population diameter structure is an important approach to revealing population structure status and regeneration strategies. The diameter structure of *P. euphratica* populations along the groundwater gradient showed similar patterns across three sections. As distance from the riverbank increased and groundwa-

ter levels decreased, populations transitioned from increasing to stable, then to declining types.

At groundwater levels  $< 2$  m (H1), the population was in the young stage (DBH  $< 4$  cm) with an average coverage of 65.4%. Seedlings (DBH  $< 2$  cm) increased, showing a pyramid-shaped age structure with 78.98% young seedlings, indicating an expanding population. At groundwater levels of 2–4 m (H2), the population structure became temporarily stable, with 46.47% of individuals  $> 4$  cm DBH and 32.33% young seedlings. As water resources continued to decrease and groundwater levels dropped, populations tended to decline due to insufficient regeneration resources.

At groundwater levels of 4–6 m (H3), young *P. euphratica* individuals (DBH  $< 4$  cm) increased to 5.38% (mostly root suckers), while 48.15% were  $> 32$  cm DBH. Population density, coverage, and stand density decreased, but average DBH and standing dead ratio reached 50.3%. The population structure showed an inverted pyramid shape with severe lack of young seedlings, indicating a declining population. As groundwater levels decreased, stands evolved from young forests to over-mature forests, with 2/3 of individuals showing poor growth vigor. Declining groundwater levels were the direct factor causing dominant population decline.

### 3.3 Response of Quantitative Characteristics to Groundwater Level Gradients

Groundwater is a crucial water source for desert vegetation survival, particularly a prerequisite for *P. euphratica* survival and growth. *P. euphratica* population density, coverage, and stand density decreased with declining groundwater levels, while mortality increased. Fitted curves for density, coverage, DBH, mortality, and stand density with groundwater levels reached extremely significant levels ( $P < 0.01$ ), indicating groundwater directly affects dominant population structure, growth vigor, and survival dynamics.

Canopy diameter showed a quadratic relationship with groundwater level ( $P < 0.01$ ). First-order derivation of this quadratic curve indicated maximum individual canopy diameter at 3.95 m groundwater level, suggesting this is the suitable survival water level for *P. euphratica* populations. Canopy diameter decreased as groundwater levels declined, indicating groundwater  $< 4$  m benefits canopy extension and growth vigor with large photosynthetic area. Population density and stand density were 8.0 and 7.05 at 7.42 m groundwater level, respectively, with mortality reaching 100% at 7–8 m groundwater level, representing the groundwater threshold for *P. euphratica* population survival.

### 3.4 Response of Hill Diversity to Groundwater Level Gradients

Species diversity of *P. euphratica* communities showed a gradual decreasing trend with declining groundwater levels. The deeper the groundwater level, the lower the diversity index. As groundwater levels declined, tree diversity

remained unchanged while shrub and herb survival resources continuously decreased. The three sections showed similar diversity index trends along groundwater gradients, with two distinct change characteristics.

At groundwater levels < 2 m, diversity index amplitude increased significantly. When  $\Delta h = 0.8$  and 2.0, diversity indices decreased by 68.1% and 11.6% compared to  $\Delta h = 0$ , respectively. At 2–4 m groundwater levels, diversity index amplitude decreased, with curves becoming flattened. When  $\Delta h = 0.8$  and 2.0, diversity indices decreased by 20% and 80% compared to  $\Delta h = 0$ , respectively. At 4–6 m groundwater levels, species diversity decreased sharply, with curves nearly linear. When  $\Delta h = 0.8$  and 2.0, diversity indices decreased by 30.31% and 43.38% compared to  $\Delta h = 0$ , respectively.

This stage showed severe species diversity reduction in the upper Tarim River due to deep groundwater levels and long-term lack of flood recharge. Drought-intolerant semi-shrubs and shrubs gradually declined and disappeared, causing sharp reductions in species types and numbers. It is predictable that when groundwater levels exceed 6 m, plant communities will degrade into sparse, declining Tamarix communities or single-dominant Tamarix communities, consistent with field survey results.

### 3.5 Response of Diversity to Groundwater Level Gradients

Diversity indices revealed changes in community structure and species composition along groundwater gradients. The  $S$  values between adjacent plots after clustering were greater than those between non-adjacent plots. The  $C$  and  $W$  indices increased with increasing habitat heterogeneity between adjacent plots, while the  $S$  index decreased.

The maximum  $S$  value appeared between plots H1 and H2, indicating similar community structure and many shared species between adjacent habitats at groundwater levels < 4 m. The  $S$  values between H2 and H3 and between H1 and H3 were 30.31% and 43.38% lower than between H1 and H2, respectively, showing that species diversity and shared species decreased significantly as groundwater levels declined.

The maximum  $C$  and  $W$  values appeared between H1 and H3, increasing gradually with groundwater level gradients. Non-adjacent plot  $C$  and  $W$  values were 103.04% and 147.47% greater than adjacent plot values, respectively. Both  $C$  and  $W$  showed extremely significant correlations with groundwater level differences ( $P < 0.01$ ), indicating that as groundwater levels decreased, community structure and species composition differences increased, community layers simplified, and species turnover rates accelerated. This reflects retrogressive succession to communities dominated by deep-rooted, drought-resistant tree and shrub species with wide ecological amplitudes.

#### 4. Discussion

Desert riparian forests dominated by *P. euphratica* along the Tarim River are characterized by their dependence on water—thriving with water and perishing without it. Since the 1950s, land reclamation and water resource utilization have reduced groundwater levels, weakened vegetation growth, and increased plant mortality, affecting sustainable agricultural development and oasis economies. Global climate warming, decreasing runoff, and human socioeconomic activities have altered water resource distribution, causing plant community development to remain in early successional stages.

As groundwater levels continue to decline, *P. euphratica* community structure simplifies and species diversity decreases, reflecting that groundwater level is a key ecological factor limiting desert vegetation distribution and survival in extremely arid regions. Studies have shown that declining groundwater levels and site drying are dominant factors causing population decline and vegetation degradation in the Tarim River basin. The relationship between vegetation evolution and groundwater level changes is complex, involving dynamic balances among groundwater, soil, and vegetation.

Various studies have explored rational ecological water levels for desert vegetation from different perspectives, including vegetation quantitative characteristics, ecophysiological responses, groundwater quality, and species niches. Chen Yaning et al. indicated that the rational ecological water level for *P. euphratica* and *Tamarix* survival is <4 m, with a critical groundwater level around 4–4.5 m. Hao Xingming et al. reported that suitable groundwater depth for plant growth and maintaining high species diversity is 2–4 m, with vegetation growth stressed and species diversity impaired at 4.5–7 m. Zhang Li et al. found that suitable ecological water levels for desert vegetation in the lower Tarim River are 2–4 m, with critical groundwater levels at 7–8 m.

From the perspective of regional vegetation restoration and ecological improvement, groundwater levels should be maintained at <6 m to keep desert riparian forests stable. Our analysis shows that rational ecological groundwater levels for vegetation restoration in the Tarim desert riparian forest are 4–6 m, consistent with previous research. When groundwater levels exceed 6 m, vegetation degrades significantly, species diversity decreases sharply, and the dominant species declines. At groundwater levels of 7–8 m, vegetation dies extensively, with living vegetation coverage <10% and stand density <0.1, representing the critical coverage for desertification. This water level can only sustain survival of individual deep-rooted vegetation but cannot achieve ecological restoration of natural vegetation.

## 5. Conclusions

*Populus euphratica* communities at different groundwater levels in the upper Tarim River can be classified into three types: groundwater levels <2 m, 2–4 m, and 4–6 m. As groundwater levels decline, desert riparian forest community structure simplifies, species composition differences increase, species diversity decreases, and quantitative characteristics of the dominant *P. euphratica* population decline. Decreasing groundwater levels are the dominant factor causing population decline and community degradation.

The groundwater level at which species diversity begins to be impaired in the upper Tarim River desert riparian forest is 4.0 m. The suitable survival groundwater level for *P. euphratica* populations is <4 m, with groundwater thresholds at 7–8 m. The rational ecological groundwater level for vegetation restoration in the Tarim desert riparian forest is 4–6 m. When groundwater levels exceed 6 m, communities degrade significantly, species diversity decreases sharply, and the dominant species becomes sparse and declines.

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