Postprint: Characteristics of Hollow Living Populus euphratica Trees at Different Stand Ages in the Middle Reaches of the Tarim River

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Abstract

Populus euphratica serves as an indicator species for ecological environmental changes in arid regions and plays an irreplaceable role in maintaining the stability of regional fragile ecosystems. This study investigated living Populus euphratica trees of different stand ages in the sample plots of the Populus euphratica Forest Ecosystem Positioning Observation and Research Station in the middle reaches of the Tarim River, exploring the hollowing rate of living trees, architectural differences between hollow and non-hollow trees, and the variation patterns of architectural traits in hollow living trees. The results show that the hollowing rate of living Populus euphratica trees in the study area was 16.96%, approximately 78 trees · hm^{-2}, and the hollowing rate increased with stand age, with the hollow incidence rate in mature trees being 4.3 times that in immature trees. The degree of hollowing in living Populus euphratica trees showed significant positive correlations with diameter at breast height, tree height, crown width, and canker area ($P<0.05$), a significant negative correlation with the height-diameter ratio, and non-significant correlations with crown sparsity and crown length ratio; the hollowing phenomenon did not cause obvious disadvantages in growth performance. With increasing stand age, the architectural traits of hollow living Populus euphratica trees exhibited resource-conservative adaptive characteristics, suggesting that hollowing is likely an adaptive strategy of Populus euphratica to extremely arid environments.

Full Text

Hollow Tree Characteristics of Different Aged Populus euphratica Forests in the Middle Reaches of the Tarim River

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Abstract

Populus euphratica Oliv. is an indicator species of eco-environmental changes in arid areas and plays an irreplaceable role in maintaining the stability of regional fragile ecosystems. This study investigated living standing trees of P. euphratica across different stand ages in the Tarim River National Positioning Observation Station of P. euphratica Forest Ecosystem to explore the hollow ratio, architectural differences between hollow and non-hollow trees, and variation patterns of architectural traits in hollow trees across different ages. The results showed that the hollow ratio of living standing P. euphratica trees in the study area was 16.96% (approximately 78 trees$\cdot$hm^{-2}), with the hollow rate increasing progressively with stand age. The hollow occurrence rate in mature trees was twice that of immature trees. The degree of hollowing in living trees was significantly positively correlated with diameter at breast height (DBH), tree height, crown width, and ulcer area ($P < 0.05$), while significantly negatively correlated with height-to-diameter ratio. No significant correlations were observed with crown loss ratio or crown length ratio, indicating that hollowing did not cause obvious growth disadvantages. As stand age increased, the architectural traits of hollow living P. euphratica trees exhibited resource-conserving adaptation characteristics, suggesting that hollowing is likely an adaptive strategy of P. euphratica to extremely arid environments.

Keywords: Tarim River; different stand ages; Populus euphratica; hollow tree; architecture traits

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1.1 Study Area Overview

The study area is located in the Luntai County Lunnan Town National Populus euphratica Nature Reserve in the middle reaches of the Tarim River (84°15 E, 41°09 N, 917 m altitude). The region experiences a typical warm temperate extremely arid desert climate with distinct seasons and cold winters. Annual sunshine duration ranges from 2442 to 2925 hours, with an average temperature of 10.9–14.6°C and extreme minimum temperature of -25.5°C. The average annual precipitation is 17.4–42.8 mm, while annual evaporation reaches 2024 mm. The frost-free period lasts 180–224 days with $ $10°C accumulated temperature of 4125.3°C. Strong north winds dominate during spring-summer transitions. The nature reserve contains the largest and least human-disturbed primary forest in China, characterized by simple community structure and low species diversity. Soils are primarily desert soil, saline-alkali soil, and aeolian sandy soil. The flora is dominated by Salicaceae, Tamaricaceae, Fabaceae, Asteraceae, and Poaceae families. Major tree species include Populus euphratica and Populus pruinosa, shrubs include Tamarix ramosissima, Halimodendron halodendron, and Lycium ruthenicum, and herbaceous plants include Phragmites communis, Glycyrrhiza inflata, Karelinia caspica, and Apocynum venetum.

1.2 Sample Plot Selection

This study utilized fixed sample plots from the National Forestry and Grassland Administration's Tarim River Basin P. euphratica Ecosystem Positioning Observation Research Station, established in accordance with the "Technical Regulations for Forest Resource Planning and Design Survey" (2003) age group classification standards. Based on field surveys of the Tarim River P. euphratica Nature Reserve, we selected standard plots in natural P. euphratica forests with similar community characteristics and consistent site conditions across different stand ages. Following Wang Shiji et al.'s classification system, we established five standard sample plot age groups: young, middle-aged, near-mature, mature, and over-mature forests. In 2021, we randomly set up 10 m × 10 m quadrats within middle-aged, near-mature, mature, and over-mature forest plots to investigate architectural traits of living P. euphratica trees. No hollow trees were found in young forest plots, so this age group was excluded from the study.

1.3 Measurement Methods

1.3.1 Age Classification

P. euphratica is an extremely endangered species with long growth cycles, making precise age determination through tree rings difficult. Although population age classes differ from diameter classes, they respond similarly to environmental conditions. Therefore, we used DBH as an indicator of age size, following previous studies on P. euphratica population structure. Based on the species' life history characteristics and Wang Shiji et al.'s age classification system, we divided living P. euphratica trees into four size classes based on DBH: young trees (5 cm $<$ DBH $\leq$ 17 cm), middle-aged trees (17 cm $<$ DBH $\leq$ 25 cm), near-mature trees (25 cm $<$ DBH $\leq$ 41 cm), and over-mature trees (DBH $>$ 41 cm).

1.3.2 Field Measurements

We measured all living P. euphratica trees with DBH $\geq$ 5 cm in each quadrat, recording architectural traits including DBH, tree height, crown width, branch height, and crown loss ratio. We also documented external decay characteristics such as position, number, and dimensions of tree holes and ulcers, photographing representative decay features. A total of 712 living P. euphratica trees were surveyed, comprising 120 hollow trees (16.96%) and 592 non-hollow trees (83.04%). Ulcer symptoms were present in 446 trees, with an ulcer occurrence rate of 62.61%.

1.3.3 Architectural Indicators

Hollow Ratio: Calculated as (Number of hollow P. euphratica trees / Total number of surveyed trees) $\times$ 100%. Following Harper et al.'s tree hole measurement method, hollow trees were defined as those with at least one hole in the trunk or branches with both vertical and horizontal widths $\geq$ 5 cm.

Tree Hole Height (THH): Distance from the ground to the tree hole.

Tree Hole Area (THA): Measured by treating the hole as circular and converting from diameter measurements.

Ulcer Height (UH): Distance from the ground to the ulcer.

Ulcer Area (UA): Measured using the same method as tree hole area. Ulcers represent tree decay and were measured following Wang Yuting et al.'s decay investigation methods for Korean pine.

Diameter at Breast Height (DBH): Measured with a diameter tape (precision $<$ 0.1 cm).

Tree Height (TH): Measured using a Blume-Leiss altimeter.

Crown Width (CW): Measured with a tape in east-west and north-south directions, using the average value.

Tree Crown Loss Ratio (TCR): Following Aishan et al.'s method for assessing P. euphratica growth in the lower Tarim River, this represents the overall proportion of canopy leaves and indicates crown growth morphology.

Height-Diameter Ratio (HDR): Ratio of tree height to DBH.

Crown Length (CL): Total length of the crown.

Crown Length Ratio (CLR): Ratio of crown length to tree height, calculated as (CL/TH) $\times$ 100%.

1.4 Data Processing

Data were processed and analyzed using Microsoft Excel 2019 and SPSS 25.0. Duncan's multiple comparison and independent sample t-tests were used to examine significant differences in architectural traits among different stand ages. Pearson correlation analysis was conducted to examine relationships among hollow tree architectural indicators, and principal component analysis (PCA) was used for comprehensive analysis. Figures were created using OriginPro 2022.

2.1 Basic Characteristics of Different Aged Stands

The hollow ratio of P. euphratica living trees increased with stand age, ranging from 6.33% in middle-aged forests to 7.84% in near-mature forests, 15.56% in mature forests, and reaching 52.38% in over-mature forests—15.6 times higher than in middle-aged forests. Ulcer occurrence rates were substantially higher than hollow rates across all age groups, ranging from 46.83% to 90.48%. Population density fluctuated considerably, with stand density decreasing significantly with age, demonstrating clear self-thinning effects. Mean and maximum DBH values increased significantly from middle-aged to mature forests, with no significant difference between mature and over-mature forests. Mean tree height ranged from 8.2–9.0 m, peaking in mature forests. Mean crown width followed the same trend as mean tree height.

2.2 Architectural Characteristics of Hollow vs. Non-Hollow Trees

We divided surveyed trees into hollow and non-hollow groups to analyze whether hollowing affected architectural traits. Results showed significant differences ($P < 0.05$) in DBH, height-diameter ratio, ulcer area, ulcer height, and tree hole area across some age groups, but no significant differences in other indicators. DBH, height-diameter ratio, and ulcer area showed consistent significant differences, indicating these three parameters are important indicators of hollowing occurrence across age groups. Hollow trees had larger DBH but lower height-diameter ratios than non-hollow trees, suggesting that hollowing did not significantly impact growth and that hollow trees maintained certain growth advantages.

2.3 Hollow Rate Characteristics Across Age Classes

Hollow rates for different age classes were analyzed by grouping all hollow trees by DBH. Middle-aged trees only occurred in middle-aged and over-mature forests, with the hollow rate in over-mature forests being 5.56 times that in middle-aged forests. Near-mature tree hollow rates showed an initial increase, then decrease, then increase again with stand age, peaking in over-mature forests at 5.56 times the rate in near-mature forests. Mature tree hollow rates increased with stand age, being lowest in near-mature forests (5.56%) and highest in over-mature forests (66.67%). Over-mature tree hollow rates increased with age class, reaching 20.4% in near-mature forests, 48.2% in mature forests, and 68.1% in over-mature forests. Overall, hollow rates increased with both stand age and

DBH (age), indicating that hollowing occurrence is closely related to developmental stage and environmental conditions.

2.4 Correlation Analysis of Hollow Tree Architectural Traits

Age class was strongly positively correlated with DBH, crown width, and ulcer area ($P < 0.001$), and negatively correlated with height-diameter ratio ($P < 0.001$). DBH was strongly positively correlated with tree height, crown width, ulcer area, and tree hole area ($P < 0.001$), but negatively correlated with height-diameter ratio ($P < 0.001$). Crown width was strongly positively correlated with ulcer area and tree hole area ($P < 0.001$), and negatively correlated with height-diameter ratio ($P < 0.001$). Height-diameter ratio was strongly negatively correlated with ulcer area and tree hole area ($P < 0.001$). Ulcer area was strongly positively correlated with tree hole area ($P < 0.001$). These results demonstrate that architectural traits of hollow trees are interrelated across different stand ages.

2.5 Principal Component Analysis of Hollow Tree Traits

The first two principal components explained 65.2% of trait variation, with PC1 accounting for 44.4% and PC2 for 20.8%. PC1 was primarily associated with growth characteristics including DBH, crown width, ulcer area, tree hole area, and height-diameter ratio, while PC2 was associated with crown length ratio, tree hole height, ulcer height, and crown loss ratio. Cluster analysis revealed distinct differences among stand ages. Middle-aged forest hollow trees showed the greatest variation along PC1, primarily influenced by height-diameter ratio. Near-mature forest hollow trees showed the greatest variation along PC2, influenced by height-diameter ratio and crown length ratio. Mature forest hollow trees tended toward the PC1-positive region, while over-mature forest hollow trees were more constrained, primarily distributed in the PC1-positive/PC2-negative region, indicating stabilization. These patterns reflect how P. euphratica adjusts growth strategies in response to changing environmental conditions across stand ages.

3.1 Distribution Characteristics of Hollow Trees

Our results show that hollow rates of P. euphratica living trees increased with stand age across all age groups, consistent with findings from Zheng et al. and Zhou et al. in the upper Tarim River, though our rates were lower than those reported by Zhou et al., likely due to better site conditions in our study area. In the lower Tarim River, where conditions are harsher with frequent streamflow interruption and lower groundwater levels, hollow rates reached 26.2% with hollow tree density 2.4 times higher than in our study area. This demonstrates that habitat quality is a key driver of hollowing. The degree of hollowing was significantly positively correlated with DBH, ulcer area, and crown width ($P <$

0.05), indicating that as trees age, ulcer area increases and hollowing intensifies while crowns continue growing. This suggests hollowing does not substantially affect tree growth, consistent with Hao et al.'s findings in Ejina. As P. euphratica ages, sapwood density and toughness increase, and while heartwood decomposes to form hollows, the functional xylem and phloem remain unaffected, allowing normal growth and physiological metabolism. Tree holes contain nutrient-rich deposits that create unique microenvironments at the base when decomposed by microorganisms, enhancing fertility and adaptation to harsh conditions.

3.2 Adaptation Strategies of Hollow Trees

In extreme environments, architectural trait variation reflects adaptive strategies to minimize environmental stress. Our PCA showed that from middle-aged to over-mature forests, hollow trees shifted rightward along PC1, indicating different response strategies to environmental conditions. Middle-aged forest hollow trees were primarily influenced by height-diameter ratio, suggesting favorable conditions promoting rapid growth. Near-mature forest hollow trees showed maximum variation in height-diameter ratio and crown length ratio, with larger crown length ratios indicating increased resource investment in branches as water, nutrient, and carbon acquisition improved. Mature forest hollow trees showed maximum variation in tree height, with the lowest crown loss ratio (38.6%) across all age groups, likely reflecting a trade-off between canopy architecture and water transport to minimize water limitation effects. Over-mature forest hollow trees showed primary variation in DBH, crown width, tree hole area, and ulcer area, with reduced tree height but unaffected crown length ratio and loss ratio, indicating photosynthetic organs were not further compromised. This resembles the safety-economic trade-off strategy observed in Salix matsudana under environmental stress, where trees increase DBH and crown width while reducing height. In over-mature forests with deteriorating resources, P. euphratica invests more resources in roots for groundwater acquisition, demonstrating a resource-conserving strategy in response to habitat degradation.

4 Conclusions

Based on investigation and analysis of hollow tree characteristics in different aged P. euphratica forests in the middle Tarim River reaches, we conclude:

1. The hollow ratio of living P. euphratica trees in the study area was 16.96% (approximately 78 trees $\cdot$ hm^{-2}). Hollow rates increased with stand age from 6.33% in middle-aged forests to 7.84% in near-mature forests, 15.56% in mature forests, and 52.38% in over-mature forests. DBH (age) and habitat conditions are the primary factors driving hollowing occurrence.

2. Hollowing did not significantly affect tree growth. Ulcer occurrence facilitates infection by wood-decay fungi, and tree hole formation is likely

a consequence of internal decay, making ulcer symptoms an important indicator that should not be overlooked.

3. As stand age increased, architectural traits of hollow living trees shifted from growth-oriented to resource-conserving adaptation characteristics. We propose that hollowing in P. euphratica living trees represents a survival strategy in response to habitat deterioration.

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