# Postprint: Retrieval of Populus euphratica Forest Structural Parameters from WorldView-2 High-Resolution Imagery

**Authors:** Yang Xuefeng

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## Abstract

Forest structure characteristics constitute critical indicators for evaluating forest ecosystems, and acquiring large-scale forest structure information through remote sensing technology is of significant scientific importance. The lower reaches of the Tarim River represent a key region for ecological protection in China' s arid zones, where Populus euphratica forests serve as the primary target of ecological restoration efforts, rendering the study of their forest structure parameters of particular practical significance. By utilizing high-resolution WorldView-2 remote sensing imagery in combination with UAV remote sensing technology, and applying spectral mixture theory and object-based image processing techniques, information on Populus euphratica tree count, crown diameter, vegetation coverage, and tree height was obtained for the lower Tarim River study area. Comparison with UAV observation data at the 1 $hm^2$ scale yielded $R^2$ values of 0.69, 0.63, 0.89, and 0.86 for crown diameter, tree height, vegetation coverage, and density, respectively, demonstrating that the integration of high-resolution imagery and UAV technology can acquire relatively accurate forest structure information at the regional scale. The final estimation of structural information for Populus euphratica forests in the lower Tarim River study area indicated a total tree count of approximately 1.05$×10^{5}$ trees, an average tree height of 7.38 m, an average crown diameter of 5.86 m, an average density of 26 trees per hectare, and an average coverage of 7.8%.

## Full Text

### Retrieval of Populus euphratica Forest Structural Parameters Based on WorldView-2 High-Resolution Imagery

**YANG Xuefeng[1,2], YE Mao[1,2], Munire Maimaiti[1,2]**

[1]College of Geographic Science and Tourism, Xinjiang Normal University, Urumqi 830054, Xinjiang, China
[2]Xinjiang Laboratory of Lake Environment and Resources in Arid Zone, Urumqi 830054, Xinjiang, China

**Abstract**

Forest structural characteristics are critical indicators for evaluating forest ecosystems, and the use of remote sensing technology to obtain large-scale forest structure information holds significant scientific research value. The lower reaches of the Tarim River represent a key region for ecological protection in China' s arid zones, where Populus euphratica forests serve as the primary target for ecological restoration. Studying the structural parameters of these forests thus carries important practical significance. This research employs high-resolution WorldView-2 remote sensing imagery, integrated with UAV remote sensing technology, and utilizes spectral mixture analysis theory and object-based image processing techniques to retrieve Populus euphratica tree count, crown diameter, fractional vegetation cover, and height information in the lower Tarim River study area. By comparing with UAV observation data at the 1 $hm^2$ scale, the results demonstrate that high-resolution imagery combined with UAV technology can accurately obtain forest structural information at the regional scale. Specifically, for crown diameter, $R^2 = 0.69$ and RMSE = 0.69 m; for tree height, $R^2 = 0.63$ and RMSE = 0.57 m; for vegetation cover, $R^2 = 0.89$ and RMSE = 2.8%; and for density, $R^2 = 0.86$ and RMSE = 9.64 trees $\cdot$ $hm^{-2}$. The final estimation of Populus euphratica forest structure in the study area indicates approximately $1.05 \times 10^5$ total individuals, with an average height of 7.38 m $\cdot$ $hm^{-2}$, average density of 26 trees $\cdot$ $hm^{-2}$, average crown diameter of 5.86 m, and average vegetation cover of 7.8%.

**Keywords:** forest structural parameters; Populus euphratica; high-resolution remote sensing; spectral mixture analysis; object-oriented image analysis

## 1. Introduction

Forest ecosystems represent the primary type of terrestrial ecosystem and play a vital role in regional ecological environments. Forest structural characteristics are important indicators for assessing forest ecological functions, directly reflecting forest growth conditions and serving as essential parameters in forestry, biology, and geoscience research, as well as critical inputs for numerous terrestrial ecological models. Forest structure is typically represented using parameters such as fractional vegetation cover, distribution density, crown diameter, tree height, and leaf area index. Compared with traditional ground survey methods, remote sensing technology enables more efficient acquisition of large-scale forest structural parameters. With advances in remote sensing technology, Light Detection and Ranging (LiDAR), Polarimetric Synthetic Aperture Radar Interferometry (PolInSAR), and Polarization Coherence Tomography can obtain forest three-dimensional structural information, though these techniques have limitations such as limited sampling range for spaceborne LiDAR, low ground sampling density, temporal decoherence issues with airborne LiDAR, and complex processing requirements. In contrast, optical remote sensing offers excellent spatial continuity measurement capabilities, and Very High Resolution (VHR) optical satellite remote sensing provides high ground resolution. However, current remote sensing research primarily focuses on vegetation classification and fractional vegetation cover retrieval using spectral reflectance and vegetation indices, with relatively few applications for large-scale forest structural parameter studies.

The Tarim River, China' s longest inland river, supports the world' s largest desert forest along its banks. The lower reaches of the Tarim River, located at the northern edge of the Taklamakan Desert, play a crucial ecological role in suppressing desertification and maintaining ecological balance in desert riparian zones. Due to natural and historical factors, downstream watercourses have dried up, lakes have vanished, and large areas of natural Populus euphratica forests have died, leading to increasingly severe ecological degradation. Since 2000, the Ministry of Water Resources and the Autonomous Region People' s Government have implemented ecological water conveyance projects in the lower Tarim River. Numerous studies have since evaluated the ecological status of the lower Tarim River region, with remote sensing-based research primarily employing Landsat TM/ETM data to retrieve vegetation cover changes using modified three-band maximum gradient difference models and pixel dichotomy models, monitoring vegetation cover dynamics including Populus euphratica forests to assess vegetation growth and recovery. Ground survey statistical analyses of vegetation restoration in the water conveyance area indicate that individual tree radial growth, dominant species biomass, density, average crown diameter, regeneration species height, crown diameter, and community coverage serve as 标志性 indicators of vegetation restoration.

Remote sensing technology for acquiring large-scale forest structural parameters represents a hot topic in forest remote sensing research. Compared with LiDAR and InSAR technologies, studies in this field are relatively scarce, particularly lacking systematic theoretical and technical practice for regional-scale forest structure retrieval. In ecological studies of the lower Tarim River, remote sensing technology is particularly advantageous for macroscopic understanding of Populus euphratica forest conditions. Previous studies have retrieved limited forest structural parameters restricted to small scales such as sample plots, failing to comprehensively reflect the current growth status of Populus euphratica in the lower Tarim River. This paper employs WorldView-2 VHR optical satellite remote sensing data, applying relevant remote sensing theories and techniques to invert key structural parameters (tree height, crown diameter, distribution density, and vegetation cover) of Populus euphratica forests in the lower Tarim River. This research extends the practical application fields of VHR remote sensing and enhances overall understanding of Populus euphratica ecology in the lower Tarim River, holding important scientific significance.

## 2. Study Area and Data

### 2.1 Study Area Overview

The lower reaches of the Tarim River refer to the river section between Daxihaizi Reservoir and Lake Taitema, bordered by the Taklamakan Desert to the west and the Kuruk Desert to the east. The Tarim River splits into eastern and western branches here, with the western branch being the old Tarim River and the eastern branch being the Qiwenkuoer River. The region features a continental warm temperate extreme arid climate with potential evaporation of approximately 2500–3000 mm and severe wind-sand hazards. Riparian forests dominated by Populus euphratica and Tamarix communities grow along both banks of the lower Tarim River, with Populus euphratica communities primarily occupying areas near the river channel and more drought-resistant Tamarix communities distributed further away. Herbaceous vegetation grows well in low-lying areas with high groundwater levels, though overall vegetation cover remains low, and soil types are primarily salinized sandy soils. The study area selected a river section near Yingsu in Ruoqiang County, with geographical coordinates of 87°59 36 –88°11 48 E and 40°22 51 –40°27 32 N, covering approximately 100 km$^2$.

### 2.2 Research Data

**2.2.1 Field Measurement Data** Within the aerial survey area, 30 Populus euphratica trees were randomly sampled for height and crown diameter measurements to validate UAV data accuracy.

**2.2.2 High-Resolution Satellite Imagery** WorldView-2 high-resolution remote sensing imagery was selected, comprising 0.5 m resolution panchromatic band and 1.8 m resolution multispectral bands (blue: 450–510 nm; green: 510–580 nm; red: 630–690 nm; near-infrared: 770–895 nm). This imagery enabled identification of Populus euphratica objects and extraction of tree count, height, crown diameter, and vegetation cover information.

**2.2.3 UAV Imagery** To calibrate heights of Populus euphratica objects extracted from WorldView-2 imagery and conduct data validation, four UAV validation areas were established in the western part of the study area (geographic location: 88°00 28.6 –88°01 10.17 E, 40°25 52.88 –40°26 27.73 N). In October 2017, large-scale UAV oblique photogrammetry was conducted in the observation area. Flight paths were planned with flight parameters set at 110 m altitude, acquiring ground image data through oblique photography with 80% forward overlap and 70% side overlap.

### 2.3 Data Processing

**2.3.1 UAV Image Processing** UAV images from the aerial survey area were processed using PIX4D mapper software. Structure From Motion (SFM) technology was employed for three-dimensional reconstruction, aerial triangulation, and point cloud densification to obtain point cloud data for the survey area. Point clouds were classified into bare soil and vegetation categories, and digital surface models (DSM) were generated through value processing. Digital elevation models (DEM) were then subtracted to generate canopy height models (CHM) for height calibration.

A total of 11,000 Populus euphratica trees were extracted from the aerial survey area, with an average tree height of 7.35 m. The coefficient of determination ($R^2$) between UAV data and 30 field measurements was 0.73 for crown diameter and 0.71 for tree height, with root mean square errors (RMSE) of 0.52 m and 0.70 m, respectively. These results demonstrate high accuracy of UAV-extracted Populus euphratica data, suitable for evaluating WorldView-2 extraction results.

**2.3.2 High-Resolution Image Processing** High-resolution remote sensing imagery is typically analyzed using Object-Based Image Analysis (OBIA) to leverage rich textural features, while Spectral Mixture Analysis (SMA) is primarily used to extract component information from hyperspectral imagery. To fully utilize both spectral and textural characteristics of WorldView-2 imagery, this study adopted a combined technical approach for processing and analysis.

**Crown Diameter and Density Extraction:** Due to spectral similarity between Populus euphratica and shrubs in WorldView-2 imagery, accurate classification through conventional methods is challenging. This study employed the "Min/Max Filter" algorithm in eCognition software to generate seed points from WorldView-2 data (Fig. 2). Tree height was extracted based on seed point locations, and the "Pixel-Based Object Resizing" algorithm was applied to generate vegetation canopy vector polygon objects (Fig. 3). ArcGIS analysis functions were then used to classify Populus euphratica canopies from vegetation backgrounds.

Land cover types were categorized into three typical endmembers: vegetation (Populus euphratica, shrubs, and herbaceous plants), soil (saline-alkali land and sandy land), and dark targets (shadows, rivers, and roads). Sample pixels were manually selected from the imagery to obtain spectral signatures for these three endmembers. Fully Constrained Least Squares (FCLS) linear spectral unmixing was performed to generate abundance maps for each endmember type. Vegetation canopy and shadow objects were obtained from vegetation and dark target abundance maps using the "Min/Max Filter" and "Pixel-Based Object Resizing" algorithms.

Since Populus euphratica trees in the study area are significantly taller than shrubs, they exhibit distinct shadow features in WorldView-2 imagery, unlike shrubs. Vegetation canopy objects adjacent to shadow objects were identified as Populus euphratica canopy objects. Finally, ArcGIS analysis functions separated Populus euphratica from other vegetation based on geometric spatial relationships between canopy and shadow objects.

**Tree Height Extraction:** Tree height, as crucial vertical structure information, is difficult to obtain directly from vertically observed optical remote sensing data. Studies have demonstrated that high-resolution imagery spectral information correlates with vegetation structure, and linear models incorporating texture, spectral, and geometric information significantly outperform spectral-only models for tree height estimation. This study extracted spectral, shape, and textural features of Populus euphratica canopies using eCognition software. After correlation analysis, eight features were selected (Table 1) to establish a tree height regression model using Multilayer Perceptron (MLP) regression. The MLP model parameters included a Sigmoid activation function, two hidden layers, and five neurons per layer. With 1,100 trees used for modeling and 10-fold cross-validation, the final model achieved $R^2 = 0.63$.

## 3. Results

### 3.1 Accuracy Analysis of Inverted Structural Parameters

Populus euphratica structural parameters obtained from UAV aerial surveys were used to evaluate the accuracy of parameters retrieved from WorldView-2 imagery. Given low vegetation cover in the study area and considering registration errors between WorldView-2 and UAV data, the aerial survey area was divided into 100 m × 100 m statistical units (total of 44 units). For each unit, average tree height, crown diameter, density, and vegetation cover were calculated from both UAV and WorldView-2 data, generating two datasets for linear regression analysis (Fig. 4).

All parameters showed strong correlations, indicating high accuracy of WorldView-2 derived data. The total number of Populus euphratica trees in the survey area was underestimated by 11.3% compared to UAV measurements, primarily because some low-stature or stressed trees could not be correctly identified and were misclassified as other vegetation types.

### 3.2 Spatial Distribution Characteristics of Populus euphratica

The study area was divided into 100 m × 100 m grids to calculate four structural parameters for each cell (Fig. 5). Populus euphratica was predominantly distributed in narrow zones near the main river channel, particularly on protruding riverbank areas, with additional distribution around abandoned river channels. Statistical analysis at 200 m intervals from the river channel revealed rapid decreases in both density and quantity with increasing distance. Within 200 m of the river channel, Populus euphratica density was 23.6 trees $\cdot$ $hm^{-2}$, accounting for 73.2% of total trees. Between 200–600 m from the channel, density decreased to 11.5 trees $\cdot$ $hm^{-2}$ (26.8% of total trees), and beyond 600 m, only 2.5% of trees remained. Vegetation cover also decreased significantly from 9.8% within 200 m to 4.9% at 200–600 m, dropping by half. Both tree height and crown diameter showed decreasing trends with increasing distance from the river channel.

The total Populus euphratica population in the study area was approximately $1.05 \times 10^5$ individuals, averaging 2,000 trees per kilometer of river channel.

### 3.3 Analysis of Populus euphratica Structural Composition

To better understand forest structure composition, tree height, crown diameter, density, and vegetation cover were statistically analyzed by class intervals (Fig. 6, Fig. 7). The results show that 55.5% of the study area had tree heights of 6–8 m, 49.52% had crown diameters of 6–8 m, 51.8% had densities below 20 trees $\cdot$ hm$^{-2}$, and 49.24% had vegetation cover below 5%. Across the entire study area, the average tree height was 7.38 m, average density was 26 trees $\cdot$ hm$^{-2}$, average crown diameter was 5.86 m, and average vegetation cover was 7.8%. As previously noted, the WorldView-2 processing approach underestimated some incomplete-canopy and low-stature individuals, resulting in slight overestimation of tree height and crown diameter and underestimation of density and cover.

## 4. Discussion

Currently, spaceborne LiDAR and PolInSAR technologies are widely applied in forest structure studies. However, in arid and semi-arid regions with low forest cover and height, these technologies are less effective. In such environments, VHR optical remote sensing can leverage its technical advantages. The lower Tarim River has low overall vegetation cover, with various shrubs and herbaceous plants widely distributed alongside Populus euphratica. In the WorldView-2 multispectral domain, some shrub spectra are similar to Populus euphratica, making identification based solely on spectral information ineffective.

This study employed WorldView-2 multispectral data for classification processing. Conventional OBIA techniques for high-resolution imagery typically use multiscale segmentation, local maximum, and seed point region growing algorithms. Multiscale segmentation determines canopy boundaries through image segmentation for individual tree identification. For example, Li Xiaojing used QuickBird and WorldView-2 imagery for individual tree crown extraction, achieving a correlation coefficient of 0.86 with field survey data. Multiscale segmentation is suitable for texture-rich multi-band high-resolution satellite or UAV imagery but is ineffective for grayscale data like CHM, where local maximum and seed point region growing methods are more appropriate. For instance, Yang Li achieved 85.9% correct tree identification using a local maximum method based on UAV-derived CHM data.

This study employed local maximum and seed point region growing methods to extract vegetation and shadow objects from endmember abundance maps. Comparison with UAV data demonstrated that the combined approach leveraging WorldView-2' s multispectral and high-resolution characteristics can achieve relatively reliable results while balancing accuracy and simplicity. Linear spectral unmixing models are also suitable for high-resolution remote sensing imagery analysis, particularly in scenarios with multiple vegetation types where multispectral data alone cannot distinguish species accurately. By simplifying the scene into typical endmembers (soil, vegetation, and shadow), processing complexity is reduced while maintaining classification accuracy.

## 5. Conclusions

This study retrieved primary structural parameters of Populus euphratica forest in a 100 $km^2$ area using WorldView-2 high-resolution remote sensing imagery, with UAV photogrammetry providing height calibration and accuracy validation. The main conclusions are:

1) This research demonstrates that crown diameter and density can be extracted from WorldView-2 VHR satellite imagery, while tree height can be retrieved through regression modeling using imagery texture, spectral, and geometric features. The integration of multiple techniques expands high-resolution satellite remote sensing applications from two-dimensional to three-dimensional information retrieval, providing an important reference for forest ecological studies.

2) Comparison of Populus euphratica structural parameters derived from WorldView-2 imagery with UAV data at the 1 $hm^2$ scale yielded $R^2$ values of 0.69, 0.63, 0.89, and 0.86 for crown diameter, tree height, vegetation cover, and density, respectively, with corresponding RMSE values of 0.69 m, 0.57 m, 2.8%, and 9.64 trees $\cdot$ $hm^{-2}$. These accuracies are sufficient for regional-scale forest structure surveys.

3) The study area contained approximately $1.05 \times 10^5$ Populus euphratica individuals, with an average density of 2,000 trees per kilometer of river channel. The forest exhibited patchy distribution, predominantly within 200 m of the river channel. Average structural parameters were 7.38 m height, 26 trees $\cdot$ $hm^{-2}$ density, 5.86 m crown diameter, and 7.8% vegetation cover. Tree height and crown diameter were slightly overestimated, while density and cover were underestimated. These data provide valuable reference for accurately understanding the overall ecological status of Populus euphratica forests in the lower Tarim River region.

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