

# Individual Tree Carbon Estimation with Integrated UAV-LiDAR and High-Resolution Optical Imagery

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## Introduction

This study investigates the integration of Unmanned Aerial Vehicle (UAV)-LiDAR and high-resolution optical satellite imagery for species-specific, tree-level biomass estimation. We propose an efficient method combining U-Net networks for tree crown extraction from very high-resolution optical imagery and the Dalponte2016 method for segmenting crowns from UAV-LiDAR point clouds. These data are integrated with machine learning models, including Random Forest and XGBoost, using LiDAR-derived structural parameters and vegetation indices from optical imagery. The approach achieved high accuracy ( $R^2 = 0.89$ ,  $rRMSE = 34\%$ ) across 53 trees, with species-specific datasets improving  $R^2$  by 25.2% and reducing  $rRMSE$  by 14.8% compared to traditional methods. SHAP analysis highlights the critical role of volume features in model performance. This multi-source remote sensing method shows significant potential for precise, large-scale forest carbon monitoring.

## Methods

◆ **Individual Tree Biomass and Carbon Stock Estimation.** UAV-LiDAR and VHR imagery are integrated to estimate individual tree biomass and carbon stock (Fig. 1).

- CHM Generation: Process UAV-LiDAR with lidR to create CHM.
- ITC Segmentation: Segment crowns using U-Net on VHR and CHM.
- Biomass Estimation: Calculate biomass from DBH and height.
- Carbon Stock Mapping: Estimate and map carbon stock using 0.5 factor.

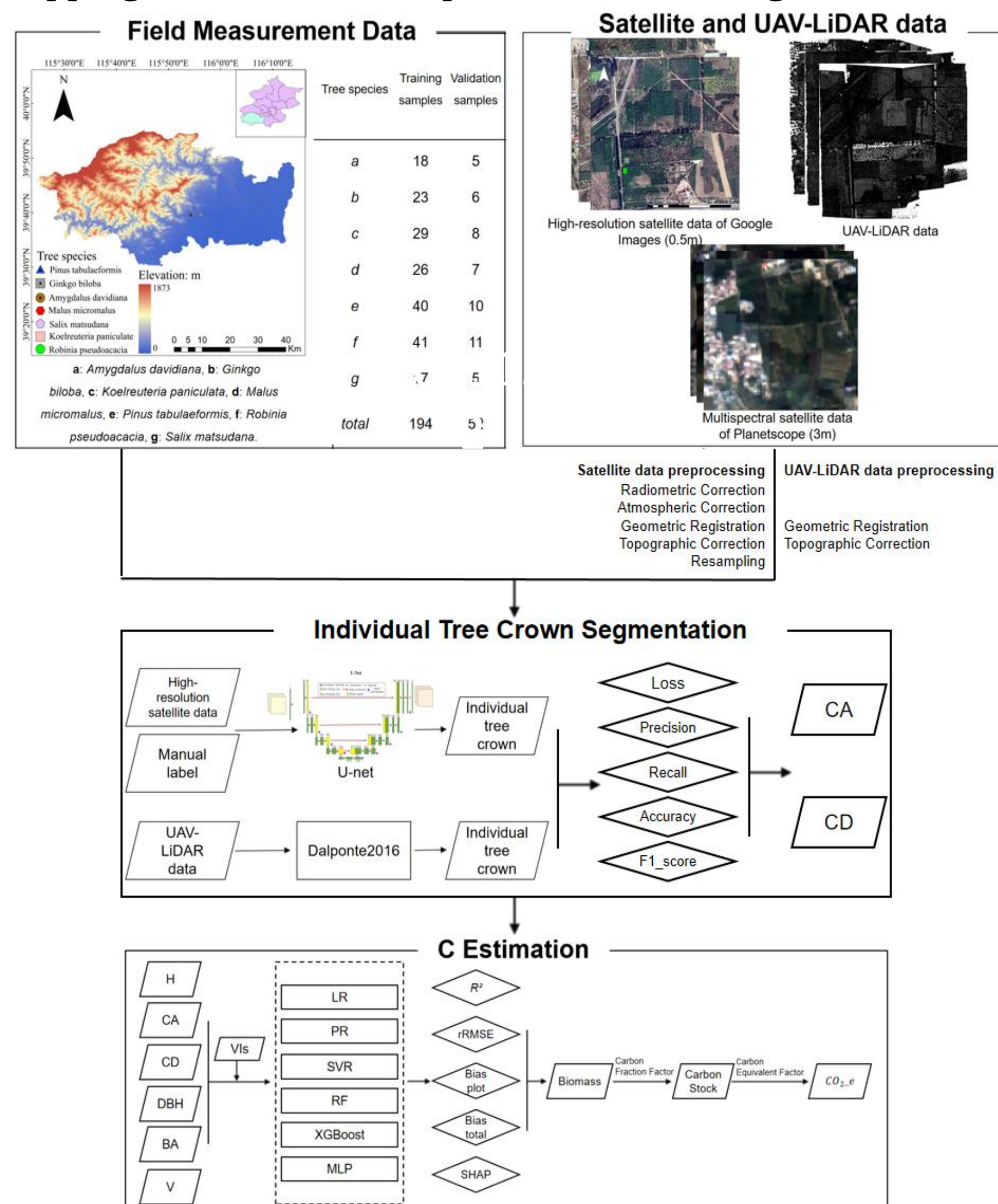


Figure 1 Flowchart of the proposed approach for the tree-level carbon mapping.

## Results

◆ **LiDAR Processing and CHM Generation (Fig. 2).**

LiDAR data were processed using lidR in R, with CSF filtering, Kriging-based DTM interpolation, normalization, and pitfree algorithm to create a CHM capturing surface feature heights.

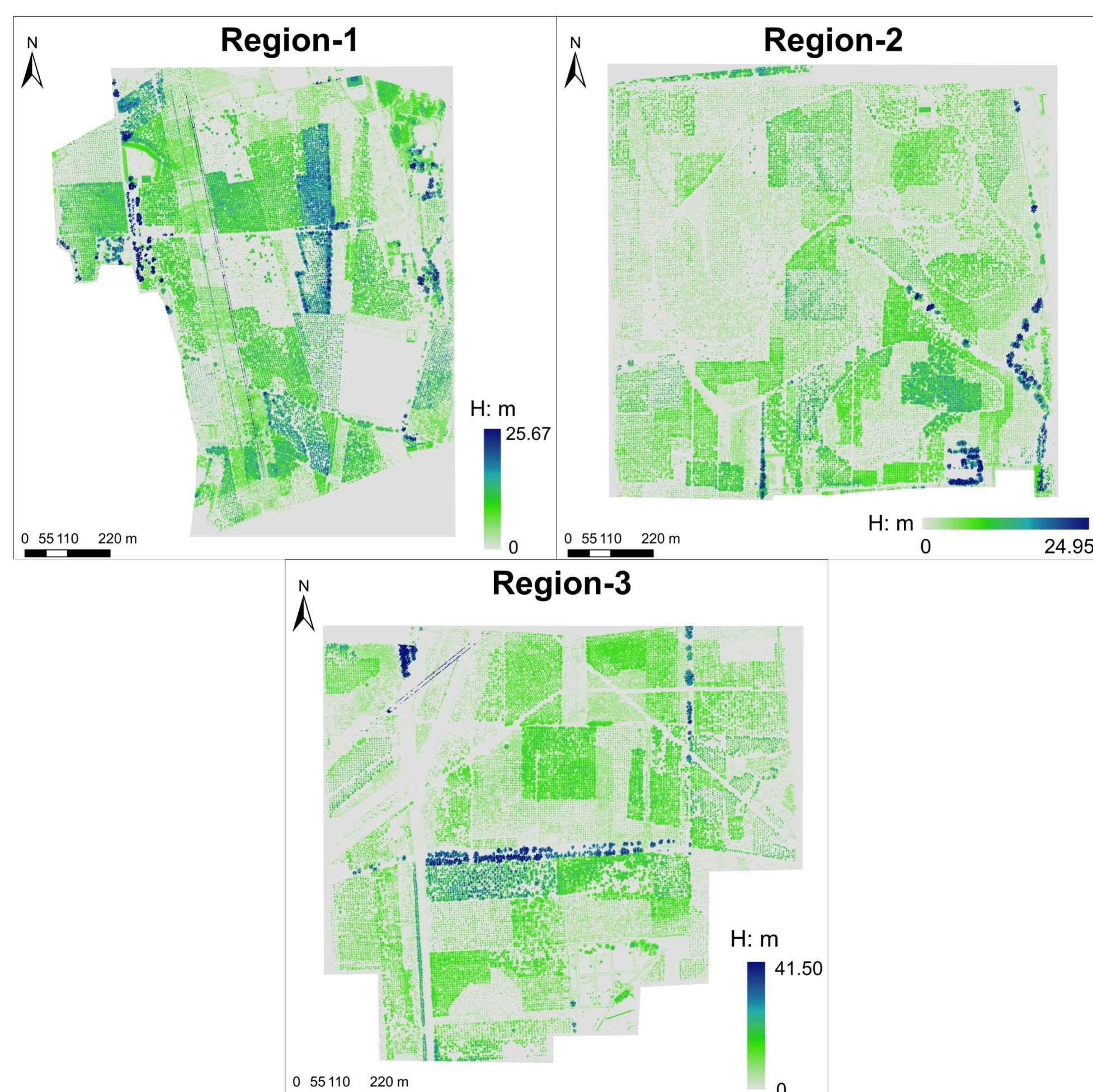


Figure 2 Canopy height map for the three study regions ranging derived from LiDAR point clouds.

## Results

◆ **Individual Tree Crown Segmentation (ITCS) Results Overview (Fig. 3).**

The U-Net model, trained for ~100 epochs, achieved effective ITCS, with loss dropping rapidly in the first 50 epochs and converging by ~80 epochs. Segmentation results from VHR images and LiDAR data were processed using lidR with CSF filtering, DTM interpolation, normalization, and CHM generation via pitfree and dalponte2016 algorithms (Fig. 3).

- VHR Image Segmentation: U-Net-based ITCS on VHR images achieves high precision (0.97–0.98) and accuracy (0.86–0.97) (Fig. 3A, C).
- Manual Annotation: Manually annotated tree crowns serve as ground truth for validating ITCS accuracy and training the U-Net model (Fig. 3B).
- LiDAR-Based Segmentation: ITCS from LiDAR point clouds, using CHM, yields F1 scores of 0.80–0.96 (Fig. 3D).

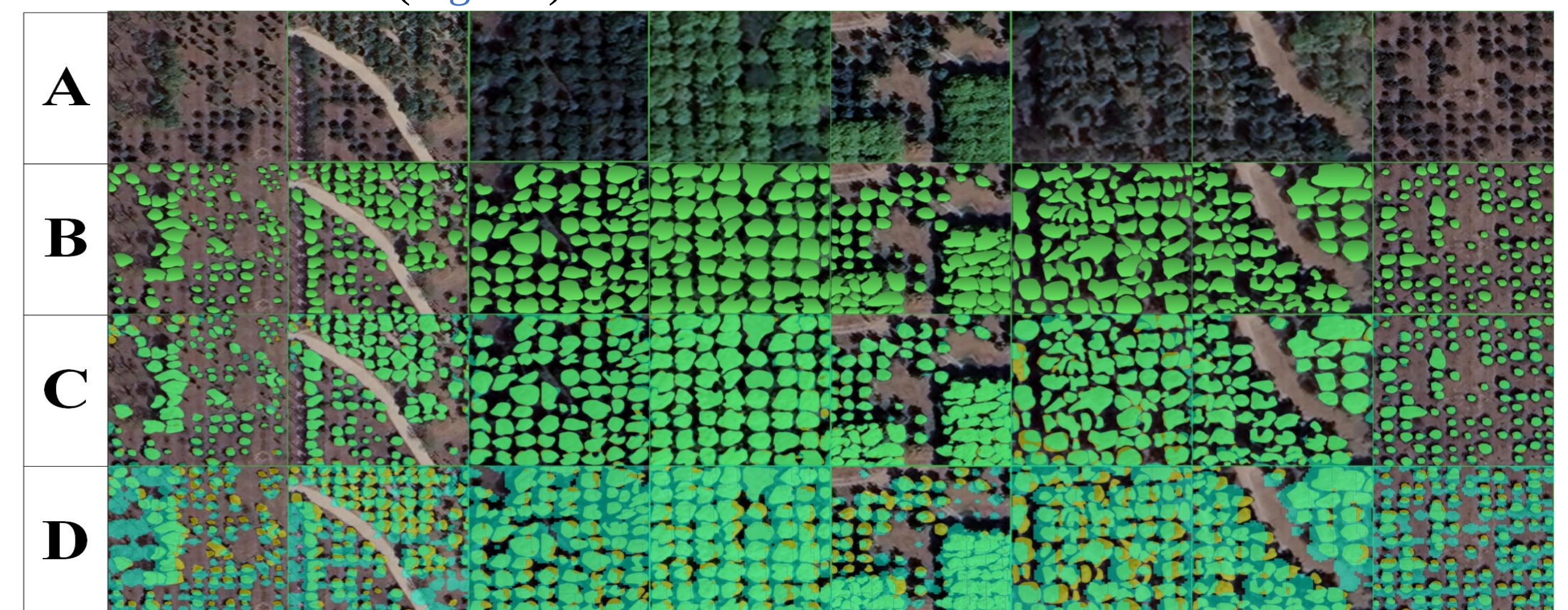


Figure 3 Individual tree crown segmentations: VHR images (A); Manual annotation (B); ITCS from VHR images based on the U-Net model (C); ITCS based on LiDAR point clouds (D).

◆ **Novel vegetation index integration boosts biomass estimation accuracy, raising  $R^2$  to 0.89 and lowering  $rRMSE$  to 0.34 for most tree species (Fig. 4).**

- For *Amygdalus davidiana* and *Pinus tabulaeformis*,  $R^2$  reaches 0.5–0.7.

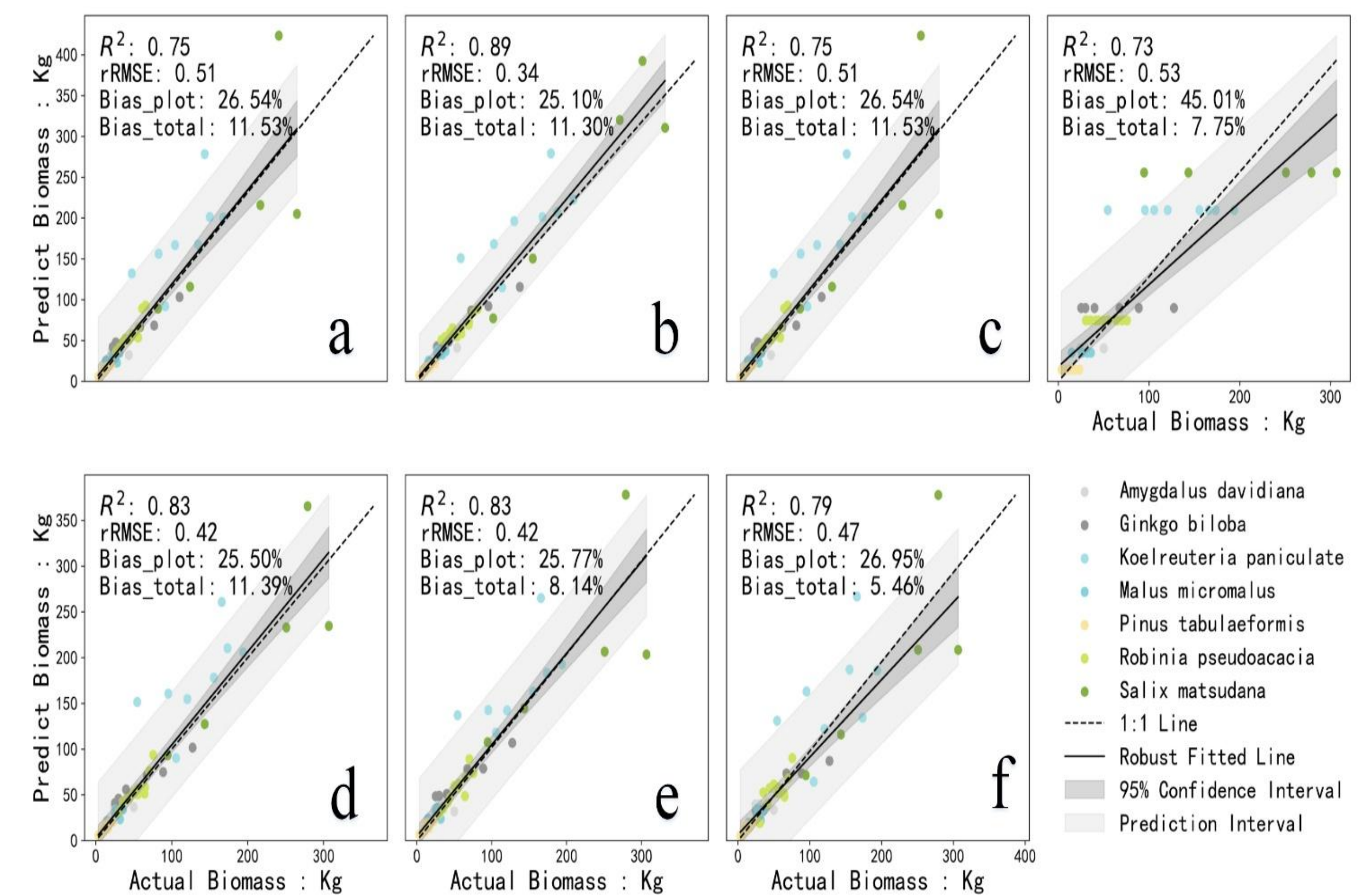


Figure 4 Multivariate biomass regression fitting results incorporating VIs, including the retrieved biomass on the entire test set for various machine learning algorithms: LR (a), MLP (b), PR (c), RF (d), SVR (e), and XGBoost (f). The first row and fourth column represent the baseline model (Mean model) results for both groups across the entire test set.

## Discussion

◆ **A biomass model mapped carbon stock (0.7–175.1 kg, mean: 19.31 kg) for 85,538 trees, with  $96.2\% \leq 47$  kg, using vegetation index-integrated regression for improved accuracy across species.**

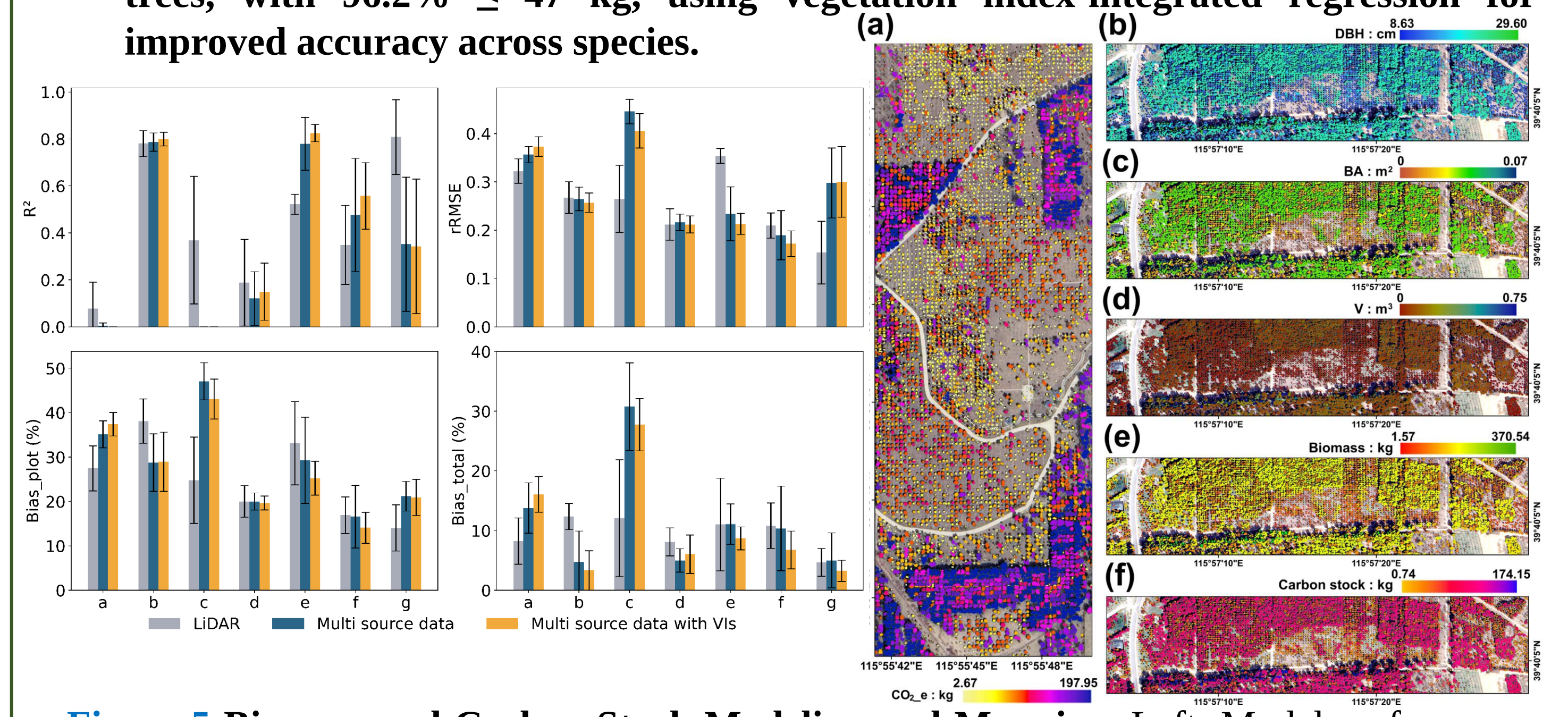


Figure 5 Biomass and Carbon Stock Modeling and Mapping. Left: Model performance for biomass estimation across seven species (a–g). Right: Maps DBH, BA, volume, biomass, carbon stock, and  $CO_2e$  for ~200 trees (a–f).