# Unmanned Aerial Vehicle-Based Carbon Sink Estimation in Bamboo and Urban Forests

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***Abstract***: *In this study, we focus on two types of landscape, urban forest and bamboo forest, carbon sink potential assessment. We combined unmanned aerial vehicle (UAV) remote sensing techniques and ground survey to establish carbon storage estimation model. We aim bamboo forest in Fuxing District, Taoyuan City and urban forest in Chunghwa Telecom Academic Kaohsiung. We set up ground survey plots to measure diameter at breast height (DBH), tree height(TH) and tree species identification in these two places to establish procedure and model feasibility. We use drone (Matrice 300 RTK) with optical sensor payload by structure from motion (SFM) and multi view stereo (MVS) methods to build canopy height model (CHM). We combine above ground biomass (AGB) and aerial forest stocking model by spatial location georeferencing to retrieve estimation value. Further, we estimate carbon storage with Intergovernmental Panel on Climate Change (IPCC) conversion factors and assess regression verification and model bias. The results display urban forest investigating 532 trees and brushes with 64.58 t C (236.79 t $CO_2$) and Phyllostachys makinoi bamboo forest demonstrating 4,299 bamboos with AGB 1,262.02 t and carbon storage 567.91 t C by 30 ground survey plots. We can save the investigation cost by using drones and it still shows good accuracy and practicality. That means UAV can be a good assist tool to estimate carbon sink value.*

*Keywords: UAV, Carbon storage, Bamboo forest, Urban forest, Structure from Motion*

## Introduction

In recent years, global climate change has emerged as an increasingly critical issue which is carbon reduction becoming a central pillar of national sustainable development strategies. Forest, as representative carbon sequestration systems, play a vital role in Environmental, Social, and Governance (ESG) assessments in carbon trading mechanisms. Within this context, carbon storage dynamics of urban forest are significantly affected by pressures from urban expansion and hillside development. Urban conservation forests have also been demonstrated to possess substantial carbon sink potential. For instance, urban forests in the United States store approximately 643 million tons of carbon, with annual sequestration rates reaching million tons (Nowak et al., 2013). Comparative studies across cities reveal a strong relationship between the productivity of urban forests and their carbon content, influenced by climate change and land cover dynamics.

Bamboo forests constitute an important component of subtropical ecosystems, owing to their rapid growth and high efficiency in carbon sequestration, thereby offering considerable potential for carbon trading. Li et al. (2018) using Landsat imagery estimated the temporal variations in aboveground carbon storage of *Phyllostachys makinoi* (Makino bamboo), demonstrating the practicality and efficiency of remote sensing techniques for large-scale bamboo carbon monitoring. In Taiwan, field investigations of *Phyllostachys makinoi* have been conducted in sample plots within the Shimen Reservoir Watershed. We measured diameter at breast height (DBH), culm height, and stand age were collected. Regression models between DBH and biomass were subsequently developed to estimate both aboveground and belowground biomass across the region. Results indicated that aboveground biomass ranged from 40.99 ton $ha^{-1}$ to 81.68 ton $ha^{-1}$, while belowground biomass was approximately 168.10 ± 23.98 ton $ha^{-1}$, highlighting the significant carbon fixation potential of *Phyllostachys makinoi.* Notably, its belowground biomass was substantially higher than that of typical broadleaf forests (Chen, 2009). These results not only provide localized benchmarks for bamboo carbon sink estimation but also validate the feasibility of combining field surveys with regression models for biomass assessment. The limitations of ground-based surveys in fragmented terrains and resource-constrained contexts, development of remote sensing techniques with large scale spatial coverage and temporal efficiency remains a core challenge in carbon sink research, which affect with direct implications for ESG assessments and carbon trading mechanisms.

Building on these insights, this study employs an integrated approach that combines UAV imagery and ground-based survey techniques to design flight protocols and operational conditions for stand-level data estimation. The objective is to evaluate and validate the carbon sequestration potential of both urban forests and bamboo forests. We developed through the integration of high-resolution imagery, point cloud generation, extraction of remote sensing variables, and aerial image interpretation, stand parameters such as crown width, TH, and canopy closure were derived. These parameters were incorporated into regression analyses to establish stem volume models and AGB models, with ground-based plot measurements applied for validation. Using the carbon conversion coefficients recommended by IPCC, both ground survey data and aerial models were converted into carbon sink estimates. This study thus proposes a practical methodological framework for UAV-based point cloud matching and remote sensing feature analysis of forest biomass. Ultimately, the integration of point cloud and remote sensing information enables the construction of aerial stand volume estimation models, supporting the quantification of forest volume, biomass, and carbon storage.

**Literature Review**

The application of remote sensing technology to stand volume estimation has become an essential method for forest resource monitoring and management. Traditional volume calculation requires measurements of DBH and TH, which is both time-consuming and costly for large-scale surveys. To address this challenge, stem volume equations and double sampling methods were developed through aerial photographs or satellite imagery. We used interpret structural parameters such as TH and canopy closure, in combination with ground plot data to establish regression models for volume estimation (Jiao, 1989; Setzer and Mead, 1988). Subsequently, the adoption of airborne LiDAR (ALS) has improved accuracy, enabling the extraction of crown dimensions, mean TH, and return information for volume modeling (Wei et al., 2010). Further, we incorporated Landsat-derived NDVI and multivariate regression to verify the potential of spectral features in volume estimation (Mouissa et al., 2013).

In recent years, advance of UAV photogrammetry, SfM point clouds, ALS, and multi-source satellite data fusion have facilitated the integration of machine learning models, such as Random Forest and Gradient Boosted Regression Trees (GBRT), into volume estimation workflows. By applying feature selection and combining structural and spectral variables, accuracy has been significantly enhanced, with coefficients of determination ($R^2$) exceeding 0.75 and root mean square error (RMSE) values of approximately 8 $m^3$/ha (Mäkinen et al., 2024). UAV-based workflows which combined with Pix4D SfM and ground control points have been shown to generate high-resolution digital surface models (DSM) and CHM, achieving TH and crown size estimation accuracies comparable to LiDAR results (Puliti et al., 2020).

Overall, stand volume estimation has evolved from early manual aerial photo interpretation and simple regression models to multi-scale modeling approaches that integrate UAV imagery, LiDAR, and multi-source satellite data. These advancements not only improve accuracy and efficiency but also demonstrate broad applicability in forest management, carbon accounting, and ecological monitoring.

Chen et al. (2009) reported that the annual carbon accumulation potential of *Phyllostachys makinoi* (Makino bamboo) is significantly higher than most afforestation tree species. Considerable capacity for carbon sequestration is underscoring. In addition, the extensive root system of *Phyllostachys makinoi* contributes to reduce soil erosion and stabilizing slopes (Lin et al., 2007). With appropriate thinning and management, the productivity of bamboo stands and their carbon sink benefits can be further improved significantly. International studies have emphasized that bamboo forests exhibit a faster rate of biomass accumulation per unit time compared to many other forest types (Christanty et al., 1996). This characteristic provided particularly evident in tropical and subtropical regions, bamboo as a forest type of strategic importance for carbon trading markets. In recent years, the bamboo forest carbon sequestration gets more attentions from academic agencies. Taiwan Forestry Research Institute and other academic institutions have conducted both modeling and field investigations of bamboo carbon sinks, providing a foundation for the development of localized carbon estimation formulas and management strategies.

## Methodology

### a. Study Area

This study established two research sites, representing an urban forest and a *Phyllostachys makinoi* (Makino bamboo) forest. The urban forest site located at the Chunghwa Telecom Training Institute in Kaohsiung, covers an area of approximately 3.6 hectares, while the bamboo forest site located in Chengfu Section, Fuxing District, Taoyuan City, encompasses approximately 33.8 hectares. Within the bamboo forest site, 30 sample plots were systematically established based on 10 × 10 m plot design. The study areas and the distribution of sample plots are illustrated in Figures 1 and 2.

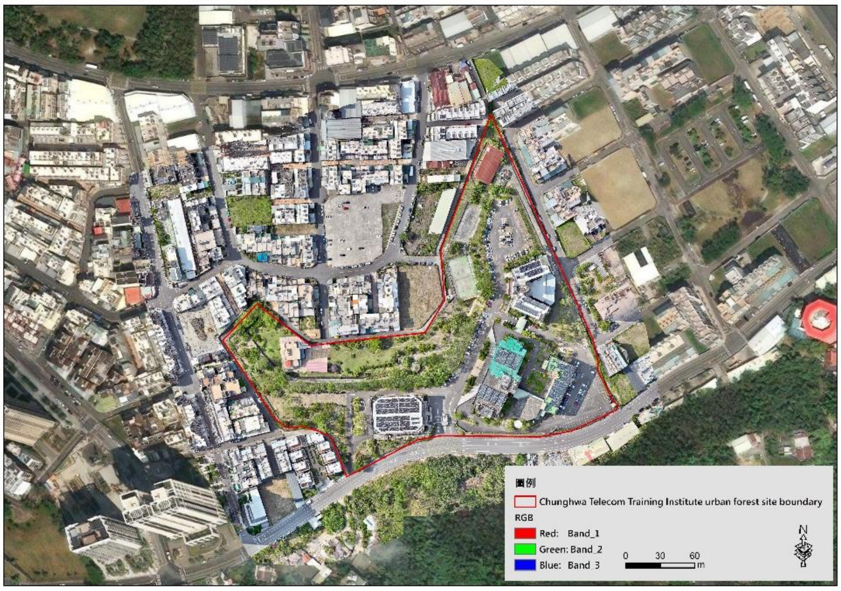


Figure 1 Chunghwa Telecom Training Institute urban forest site boundary

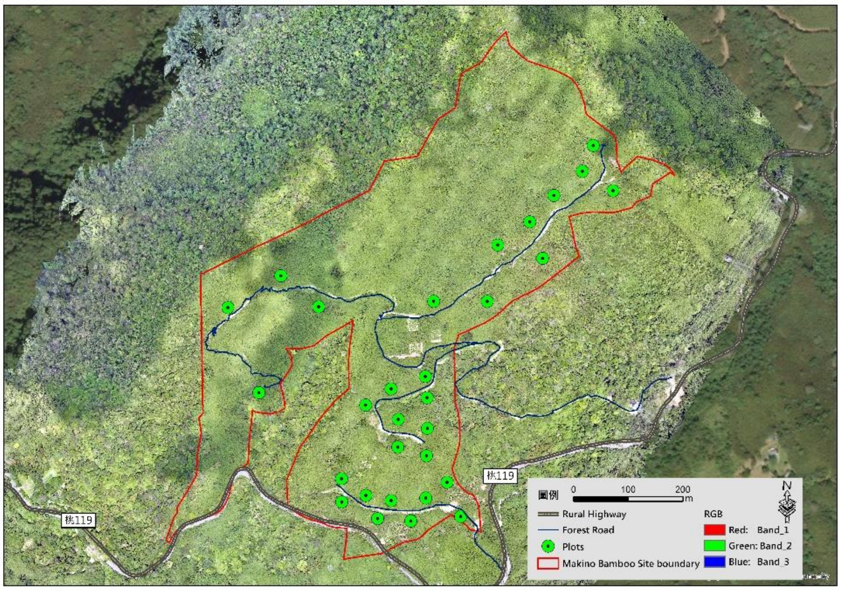


Figure 2 Makino Bamboo Site boundary in Fuxing district, Taoyuan City.

The Chunghwa Telecom Training Institute site in Kaohsiung is located near Chengqing Lake. According to meteorological data from the Kaohsiung weather station of the Central Weather Bureau, the area receives an average annual precipitation of approximately 2,000 mm, primarily concentrated between May and September. The *Phyllostachys makinoi* (Makino bamboo) study site, situated in the mountainous region on the southwestern slope of the Xueshan Mountain Range, experiences an average annual precipitation of approximately 2,000–4,000 mm based on data from Fuxing weather station with a mean annual temperature of around 22.6°C.

## b. Study Material

(a) UAV and sensors

The UAV employed in this study was the Matrice 300 RTK (hereafter referred to as M300), equipped with a P1 camera and a LiDAR sensor (Figure 3). A key feature of the M300 represents its modular design integrated with Real-Time Kinematic (RTK) positioning technology. Through aerial scanning and imaging of the study plots, the system generated both point cloud data and orthophotos (Table 1).

Figure 3 Matrice 300 RTK drone before taking off.

Table1 Matrice 300 RTK equipment specification

| Specification | Value |
|---|---|
| Wheelbase | 895 mm |
| Unladen weight | 3,600 g |
| Maximum payload | 2.7 kg |
| Maximum pitch angle | 30° |
| Maximum flight altitude | 7,000 m |
| Maximum flight endurance | 55 minutes |
| Maximum wind resistance | 15 m/s |

(b) Real-Time Kinematic (RTK) Positioning

Global positioning was conducted by using Real-Time Kinematic (RTK) technology, with coordinates recorded in the Taiwan Datum 1997 (TWD97) Transverse Mercator Coordinate System. For the urban forest sites, the position of each tree was recorded at the tree base, with adjustments made according to field conditions. These spatial records were compiled to facilitate tree position verification and map construction. For the bamboo forest site, plot coordinates were recorded to enable subsequent comparison with aerial imagery data.

(c) Basic Data of Urban Fores and Bamboo Forest

In the urban forest site, measurements were conducted by using a diameter tape and a handheld laser rangefinder (Leica DISTO D810 Touch) to collect data on tree DBH, TH, and species classification for each individual tree. In the bamboo forest site, the same equipment was used to measure culm diameter and height. A total of 30 ground plots were established to record culm number, culm diameter, culm height, and culm age of *Phyllostachys makinoi*.

(d) Model Accuracy Assessment

Point cloud data obtained from the airborne LiDAR scanning system were processed using both semi-automated and automated approaches to extract tree structural attributes. The measured stem volume from ground sample trees was used as reference data for accuracy assessment. Regression analysis and one-way analysis of variance (ANOVA) were applied to examine the relationships between field-measured stem volume and LiDAR-derived models, as well as the consistency of structural attributes derived from point cloud data. Model accuracy was evaluated using the Root Mean Square Error (RMSE), calculated as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$$

$\hat{y}_i$ : Volume estimated value, $y_i$ : Volume measurement value

(e) Stand Biomass and Carbon Storage Analysis

The calculated stem volumes were incorporated into the biomass and carbon storage equations and conversion factors published by IPCC (2019) to derive the biomass and carbon stocks of standing trees.

$AGB = V \times \mathrm{D} \times BEF$

$C = AGB \times \mathrm{CF}$

AGB: aboveground biomass, V: volume measurement value, D: wood density coefficient, BEF: biomass expansion factor, C: carbon storage, CF: carbon fraction

**c. Plot Establishment and UAV Image Acquisition**

Ground sample plots were established at the Chunghwa Telecom Training Institute in Kaohsiung and in the *Phyllostachys makinoi* (Makino bamboo) forest located in Chengfu Section, Fuxing District, Taoyuan City. These sites represented urban forest and bamboo forest conditions, respectively. At the same time, UAVs were employed to capture high-resolution orthophotos and retrieved point cloud scanning of the study areas.

(a) Plot Establishment

In the urban forest site, a complete census was conducted for all trees with a DBH value bigger than 6 cm, covering an area of approximately 3.6 hectares. In the bamboo forest, with a total area of about 33.8 hectares, 30 sample plots of 10 m × 10 m each were established randomly. Data of culm number, culm diameter, culm height, and culm age were collected for each plot.

(b) UAV Image Acquisition

Image acquisition was carried out using a DJI M300 RTK drone. Flight missions were planned through the DJI Pilot App, employing a grid-based orthophoto collection mode combined with a terrain-following relative altitude control mode to accommodate the diverse topographic conditions of bamboo forests and urban green spaces in order to generate DSM.

For the bamboo forest site, although the actual forested area was 33.8 hectares, the UAV survey covered approximately 100 hectares to account for elevation differences in the surrounding terrain and ensure accurate boundary modeling. The planned flight altitude was 150 m. For the urban forest site, with an actual area of 3.6 hectares, the UAV survey covered about 10 hectares, taking into account building obstructions and the distribution of green spaces. The planned flight altitude was 60 m above sea level. These operations were designed to retrieve centimeter-level resolution imagery, thereby improving object classification and canopy interpretation accuracy and providing essential data for subsequent digital terrain model (DTM) construction and point cloud generation.

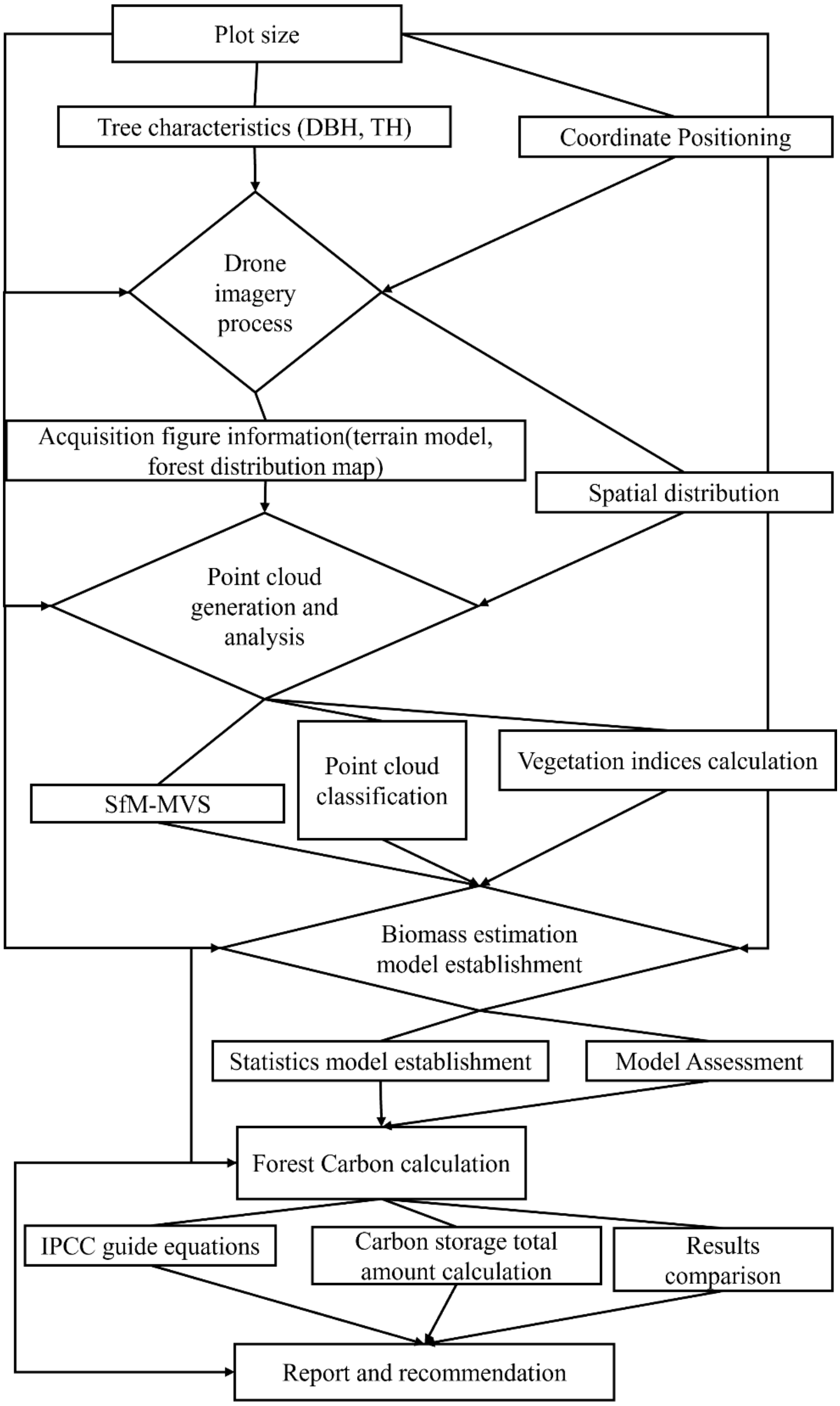

Figure 4 Study flowchart

## Results and Discussion

### a. Results of Urban Forest Research

(a) UAV Image Acquisition and Analysis of the Urban Forest

In this study, UAV aerial surveys of the urban forest covered an area of approximately 9.6 hectares. The flights were conducted at an altitude of 59 m above sea level with a single flight duration of 10 minutes and 15 seconds when 148 images were captured. Detailed flight parameters are presented in Table 2. The survey area encompassed the entire green space and successfully acquired centimeter-level resolution imagery, which served as the foundation for the generation of the DSM, DEM, and CHM.

Table2 Urban forest flight parameters

| Parameter | Setting Value |
|---|---|
| Orthophoto Ground Sampling Distance (GSD) | 1.58 cm/pixel |
| Point cloud density | 250 points/m² |
| Flight altitude (above ground level) | 59 m |
| Safe takeoff altitude | 20 m |
| Flight speed along route | 10 m/s |
| Photo capture mode | Equal distant interval |
| Forward overlap ratio | 61% |
| Side overlap ratio | 70% |
| LiDAR side overlap ratio | 50% |
| Takeoff speed | 15 m/s |

(b) Ground Survey of Urban Forest and Estimation of Individual Tree Biomass and Carbon Storage

In the urban forest site at Chunghwa Telecom Training Institute in Kaohsiung, we measure every trees and we classified tree species, DBH, TH, and tree position. For the assessment of carbon sequestration potential based on ground survey data, this study applied commonly used tree volume estimation models from the literature (Yang et al., 1961; Liu et al., 1964; Liu, 1981; Lo et al., 1986). Depending on species characteristics, appropriate stem volume equations developed in Taiwan were applied, with DBH and TH serving as the principal variables to calculate tree stem volume (V).

The estimated total stem volume of the study site was approximately 170.55 m³. Using conversion coefficients recommended by IPCC of total above-ground biomass was estimated at 137.42 t, corresponding to a carbon storage of 64.58 t C, which is equivalent to approximately 236.79 t of $CO_2$ storage.

During the process of biomass and carbon estimation, certain ornamental or landscape tree species recorded within the sample plots. According to the lack of local species-specific volume equations established in Taiwan, we use general equation to estimate tree volume to ensure consistency and practical applicability in estimation. These species were classified according to morphological characteristics as either broadleaf trees (e.g., *Alstonia scholaris, Roystonea regia, Ficus spp*.) or coniferous trees (e.g., *Juniperus chinensis*, *Platycladus orientalis*, *Araucaria heterophylla*). For these groups, we generalized equations developed in previous studies. For tree species with established local stem volume equations, such as *Cinnamomum camphora* and *Swietenia macrophylla*, the corresponding models were prioritized estimating for volume, biomass, and carbon storage estimation (Equations 1–4).

$$\text{Broadleaf trees } V = 0.0000464 \cdot DBH^{1.53578} \cdot H^{1.50657} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{Equation 1}$$

$$\text{Coniferous trees } V = 0.0000625 \cdot DBH^{1.77924} \cdot H^{1.05866} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{Equation 2}$$

$$Cinnamomum\ camphora\ V = 0.0000489823 \cdot DBH^{1.60450} \cdot H^{1.25502} \cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{Equation3}$$

$$Swietenia\ macrophylla\ V = 0.01 - 0.00871296 \cdot DBH + 0.00060626 \cdot DBH^2 + 0.0004781 \cdot DBH \cdot H \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{Equation4}$$

(c) Analysis of TH and Crown Width from Aerial Imagery and Estimation of Urban Forest Volume

TH estimation was conducted using airborne LiDAR, which provides multi-return echo characteristics. Echoes classified as single or first returns were used to generate DSM by extracting the maximum elevation point within each grid cell. Ground-classified returns were used to generate DEM. By subtracting the DEM from the DSM, CHM was generated which is representing the surface elevation of vegetation and canopy structures.

GPS-based tree position data were then overlaid with the CHM to obtain individual TH. Crown widths were delineated through image interpretation. Stem volume measured from field data was used as the dependent variable, while TH and crown width served as independent variables to construct aerial-based volume equations. As DBH and TH are the principal factors influencing stem volume, both single-variable and two-variable regression models were developed. All seven models were tested, as summarized in Table 3.

Table 3 Urban forest regression model

| Model equation | Regression Model | $R^2$ | RMSE |
|---|---|---|---|
| 1.$V=a+b\times(H^2)$ | $V=-0.019675+0.003029\times(H^2)$ | 0.57 | 0.1588 |
| 2.$V=a\times(H^b)$ | $V=0.002099\times(H^{2.126259})$ | 0.57 | 0.1590 |
| 3.$V=a\times(CW^b)\times(H^c)$ | $V=0.002287\times(CW^{0.462905})\times(H^{1.785912})$ | 0.62 | 0.1657 |
| 4.$V=a\times(CW^b)$ | $V=0.026713\times(CW^{1.373468})$ | 0.30 | 0.2220 |
| 5.$V=a+b\times(CW^2)\times H$ | $V=0.075230+0.000655\times(CW^2)\times H$ | 0.43 | 0.2307 |
| 6.$V=a+b\times CW+c\times(CW^2)\times H$ | $V=0.139277-0.023367\times CW+0.000830\times(CW^2)\times H$ | 0.44 | 0.2307 |
| 7.$V=a+b\times(CW^2)$ | $V=0.061799+0.006626\times(CW^2)$ | 0.29 | 0.2359 |

Using 68 individual trees from the urban forest dataset, this study compared stem volume estimation models. The independent variables included crown width (CW) and TH, while field-measured stem volume served as the dependent variable. Seven different regression models were tested, and model performance was evaluated using Root Mean Square Error (RMSE) as the primary indicator. Particularity, the first and second model achieved RMSE values of 0.1588 $m^3$ and 0.1590 $m^3$, respectively, which were significantly better than those of other models. These results demonstrated that, TH in this dataset provides far greater explanatory power for stem volume than crown diameter. Combining TH and CW or relying solely on crown diameter leads to reduced estimation accuracy.

The RMSE results revealed that models using TH as the sole explanatory variable performed best.

In summary, the results of this study indicate that, in the absence of DBH or other stem morphological parameters, TH can serve as a robust single predictor of stem volume in urban forests. Nevertheless, future models incorporating DBH and canopy structural indicators—such as canopy depth or LiDAR-derived height percentiles—hold significant potential for improving estimation accuracy further.

In conclusion, the findings of this study demonstrate that, in the absence of diameter at breast height (DBH) or other stem morphological parameters, TH can serve as a reliable single predictor of stem volume in urban forests. However, the incorporation of DBH and canopy structural indicators—such as canopy depth or LiDAR-derived height percentiles—offers considerable potential for improving model accuracy in the future.

**b. Results of Bamboo Forest Study**

(a) UAV Image Acquisition and Analysis of the Bamboo Forest

The actual area of the bamboo forest site was 33.8 hectares. Taking into account flight path planning and boundary requirements, the UAV survey covered approximately 80 hectares. Flights were conducted at an altitude of 120 m above ground level, with a single flight duration of 28 minutes and 14 seconds. A total of 390 images were captured. Detailed flight operation parameters are provided in Table 4. These data serve as the basis for subsequent terrain modeling and point cloud generation analyses.

Table 4 Makino Bamboo forest sites flight parameters in Fuxing district, Taoyuan City

| Parameter | Setting Value |
|---|---|
| Orthophoto Ground Sampling Distance (GSD) | 3.76 cm/pixel |
| Point cloud density | 197 points/$m^2$ |
| Flight altitude (above ground level) | 120 m |
| Safe takeoff altitude | 20 m |
| Flight speed along route | 10 m/s |
| Photo capture mode | Equal distant interval |
| Forward overlap ratio | 37% |
| Side overlap ratio | 70% |
| LiDAR side overlap ratio | 20% |
| Takeoff speed | 15 m/s |

(b) Ground Survey and Biomass Estimation of the Bamboo Forest

The bamboo forest study site was located in Fuxing District, Taoyuan City, belongs to Hsinchu Branch of the Forestry and Nature Conservation Agency. The dominant species in this area is *Phyllostachys makinoi* with a full area of approximately 33.8 hectares. 30 ground plots, each measuring 10 × 10 m, were randomly established to encompass diverse topographic and stand conditions. Within each plot, culm diameter and culm height were measured and GPS coordinates were recorded to facilitate subsequent spatial matching and modeling.

To calculate representative biomass, relevant literature was reviewed, and biomass estimation formulas applicable to *Phyllostachys makinoi* under similar site conditions were adopted (Chen et al, 2009). Based on the environmental characteristics and current stand conditions of the study area, a biomass equation developed for bamboo stands in central and northern Taiwan was selected to estimate above-ground biomass and carbon storage potential within the sample plots. Equation (5) provides a DBH-based model for estimating above-ground biomass which is suitable for bamboo stands at similar elevations and environmental conditions, and can serve as a reference for establishing regional carbon sink parameters (Equation 5).

$Y_{above} = 0.0771 \cdot DBH^2 + 0.5449 \cdot DBH - 1.575 \quad R^2 = 0.857 \cdots$ Equaion 5

Based on random sampling, a total of 30 *Phyllostachys makinoi* plots were established in the bamboo forest site, with a cumulative count of 4,299 culms recorded. Total AGB measured was 11.20 t which indicating that the bamboo forest in this area possesses strong productivity and storage capacity. The average biomass per culm was approximately 2.61 kg, representing favorable growth conditions for individual bamboo culms.

From the ground survey data, the 30 sample plots covered a total area of 0.3 ha, with a combined above-ground biomass of 11.20 t. Extrapolating this to the entire bamboo forest area of 33.8 ha in Fuxing District, Taoyuan City, the total AGB was estimated at approximately 1,262.02 t. Applying the IPCC carbon conversion coefficient of 0.45, the corresponding total carbon storage was calculated to be around 567.91 t C. These results displayed the high carbon sequestration potential and sustainable management value of the bamboo forest in this region. The mean AGB was estimated at 37.34 t/ha, further confirming that this site represents a high-potential bamboo forest area. The average AGB value also correspond to commonly observed range for *Phyllostachys makinoi* forests in central and northern Taiwan. That provides an important benchmark for the establishment of regional carbon sink parameters.

(c) Analysis of Vegetation Indices from Aerial Imagery and Estimation of Bamboo Forest Stand Volume

In this analysis, bamboo stand volume served as the dependent variable, while the average height of culms within the 30 sample plots—derived from point cloud data—was used as the independent variable. Canopy closure was calculated from UAV imagery by delineating crown positions and applying vegetation-related indices. Utilizing the spectral reflectance properties of vegetation, vegetation indices based on visible bands (R, G, B) were analyzed. Given the relatively high cost of multispectral sensors and the greater accessibility of visible-light sensors, this study adopted the Excess Green Index (ExG) for UAV image spectral analysis and canopy closure estimation (Woebbecke et al., 1995).

In this method, pixel values below 90 were classified as shadowed areas while values above 90 were classified as crown areas. Canopy closure was then calculated as the ratio of crown area to plot area, expressed as a percentage, and subsequently incorporated as a variable in the modeling of bamboo stand volume derived from aerial data. The resulting aerial-based stand volume estimates were compared against ground-measured stand volumes to evaluate estimation error.

$ExG = 2 \times G - R - B \cdots\cdots\cdots$ Equation 6

Table 5 Makino Bamboo Regression Model

| Model equation | Regression Model | $R^2$ | RMSE |
|---|---|---|---|
| 1.$V=a+b\times(H^2)$ | $V=-0.019675+0.003029\times(H^2)$ | 0.13 | 0.2027 |
| 2.$V=a\times(H^b)$ | $V=0.002099\times(H^{2.126259})$ | 0.12 | 0.2030 |
| 3.$V=a\times(CD^b)\times(H^c)$ | $V=0.002287\times(CD^{0.462905})\times(H^{1.785912})$ | 0.51 | 0.1361 |
| 4.$V=a\times(CD^b)$ | $V=0.026713\times(CD^{1.373468})$ | 0.47 | 0.1557 |
| 5.$V=a+b\times(CD^2)\times H$ | $V=0.075230+0.000655\times(CD^2)\times H$ | 0.47 | 0.1626 |
| 6.$V=a+b\times CD+c\times(CD^2)\times H$ | $V=0.139277-0.023367\times CD+0.000830\times(CD^2)\times H$ | 0.45 | 0.3912 |
| 7.$V=a+b\times(CD^2)$ | $V=0.061799+0.006626\times(CD^2)$ | 0.42 | 0.1580 |

To evaluate the applicability of different aerial-based stand volume estimation models, eight independent plots were selected as validation datasets. The statistical performance of each model on the validation data is summarized in Table 5. RMSE results ranged from 0.136 to 0.391 $m^3$, while the coefficient of determination ($R^2$) ranged from 0.12 to 0.51. Among these models, the regression model 3 demonstrated the best performance which is achieving RMSE = 0.136 $m^3$ and $R^2$ = 0.51 in the validation plots. This result indicates that incorporating both canopy density (CD) and mean TH derived from point cloud data substantially improves the explanatory power of stand volume estimation. In contrast, the combined model achieved an $R^2$ =0.45 but an RMSE=0.391 $m^3$, displaying insufficient explanatory power in structurally heterogeneous bamboo stands.

Other single-variable models—such as those using only canopy closure or mean point cloud height as predictors—performed poorly with $R^2$ values generally between 0.12 and 0.13 and RMSE values exceeding 0.20 $m^3$. These results demonstrate that a single structural parameter is inadequate for effectively capturing stand volume variability in bamboo plots. This finding is consistent with previous research, which demonstrated that composite structural factors are more reliable than single factors for explaining stand volume (Zhao et al., 2018).

Moreover, more complex polynomial models, such as the three-factor form model 6 showed moderate explanatory ability ($R^2 = 0.45$) but higher RMSE value = 0.391 $m^3$. This suggests that while multi-factor models are generally more effective than single-variable models in capturing stand volume variability, however complex models may impact from instability or overfitting in heterogeneous bamboo environments.

Overall, the validation results of this study indicate that CD and TH are the primary driving factors, and their combination can significantly enhance model predictive power. Single-variable models lack stability and are unable to accurately capture the variability of bamboo stand height and volume. Although the best-performing model achieved an $R^2 = 0.51$, leaving part of the variation unexplained, RMSE was as low as 0.136 $m^3$ at the 10 × 10 m plot scale. This level of accuracy demonstrates practical applicability and supports the estimation of bamboo forest carbon sinks and biomass resources.

**Conclusion**

This study integrated drone imagery and ground survey data to develop estimation models of AGB and carbon storage for two distinct forest types: urban forests and *Phyllostachys makinoi* forest. Furthermore, the applicability and limitations of aerial stand volume models across these forest types were examined.

In the urban forest site, ground surveys using DBH and TH were combined with locally developed stem volume equations. The total stem volume was estimated at 170.55 $m^3$, corresponding to a total above-ground biomass of 137.42 t and carbon storage of 64.58 t C (equivalent to approximately 236.79 t $CO_2$), demonstrating the potential carbon sink function of urban forests. Among the seven aerial stand volume models constructed using ground and UAV-derived data, the best performance was achieved by regression model 1and model 2 by using TH as the sole predictor with RMSE values = 0.159 $m^3$. These results indicate that TH can serve as a reliable predictor in the absence of DBH data. However, models incorporating CW derived from image interpretation performed poorly, likely because many urban trees are heavily pruned, causing discrepancies between image-based crown structures and actual stem distribution. This discrepancy reduced the correspondence between image-derived features and true stem volume, thereby lowering model accuracy.

In Makino bamboo forest site, 30 plots of 10 × 10 m were established with total 4,299 culms recorded. AGB of the sample plots was 11.20 t, extrapolated to an estimated 1,262.02 t for entire 33.8 ha study area. The corresponding carbon storage was calculated at 567.91 t C, underscoring the significant carbon sequestration potential of bamboo forests in middle scale and small-scale mountainous regions. For aerial-based modeling, regression models incorporating CD and mean height derived from point cloud data achieved the best explanatory power by process with model 3 ($R^2$=0.51, RMSE=0.136$m^3$). By contrast, models using only single variables (no matter TH or CD) exhibited low explanatory power ($R^2 < 0.15$), highlighting the limitations of single-parameter approaches in structurally heterogeneous bamboo stands. These results are consistent with Pan et al. (2023), who reported that integrating RGB imagery with machine learning regression achieved comparable accuracy ($R^2 = 0.53$, RMSE = 0.15 t/plot), further supporting the effectiveness of composite structural variables in improving volume estimation accuracy.

Above all comments, this study demonstrates the feasibility of constructing aerial stand volume models for both urban and bamboo forest. While the proposed models still require improvement, the results validate the potential of integrating UAV and ground-based surveys in carbon quantification efforts. Future research should incorporate high-resolution LiDAR and multispectral vegetation indices to enhance cross-site applicability, improve monitoring of carbon storage dynamics, and strengthen carbon sequestration potential assessments. Such advancements will provide critical support for carbon inventory initiatives and the practical implementation of ESG-related carbon trading mechanisms in Taiwan.

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