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Estimation of the aboveground biomass and carbon sequestration in an urban forest remnant using aerial photogrammetry from a low-cost Unmanned Aerial Vehicle

CHATCHARIN PENBOON[1,2], SORAVIS SUPAVETCH[3], KAMPANART SIRIRUEANG[4], SASIWIMOL RINNAMANG[4], PHANUMARD LADPALA[5], THARNRAT KAEWGRAJANG[6], PONTHEP MEUNPONG[7,♥]

[1]Faculty of Forestry, Kasetsart University, Bangkok 10900, Thailand
[2]Information and Communication Technology Center, Department of National Parks, Wildlife and Plant Conservation, Bangkok 10900, Thailand
[3]Department of Civil Engineering, Faculty of Engineering, Kasetsart University, Bangkok 10900, Thailand
[4]World Wildlife Fund, Phaya Thai, Bangkok, 10400, Thailand
[5]Forest and Plant Conservation Research Office, Department of National Parks, Wildlife and Plant Conservation, Bangkok 10900, Thailand
[6]Department of Forest Biology, Faculty of Forestry, Kasetsart University, Bangkok 10900, Thailand
[7]Department of Silviculture, Faculty of Forestry, Kasetsart University. 50 Ngamwongwan Rd, Lat Yao, Chatuchak, Bangkok 10900, Thailand. Tel.: +66-257-90176, Fax.: +66-294-28107, ♥email: fforptm@ku.ac.th

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Abstract. *Penboon C, Supavetch S, Sirirueang K, Rinnamang S, Ladpala P, Kaewgrajang T, Meunpong P. 2023. Estimation of the aboveground biomass and carbon sequestration in an urban forest remnant using aerial photogrammetry from a low-cost Unmanned Aerial Vehicle. Biodiversitas 24: 1908-1915.* For low-income nations, a low-cost Unmanned Aerial Vehicle (UAV) offers an alternative to the traditional time-intensive forest survey that requires many resources. This study was conducted in the remnant forest with the dominant tree species, *Dipterocarpus alatus* Roxb., forming the upper canopy. Photogrammetry techniques with UAV images were used to obtain the Canopy Height Model (CHM). The results of tree height, individual tree detection, biomass, and carbon sequestration were compared between ground truthing and photogrammetry estimation. The large percentages of trees were automatically recognized. However, due to a closed forest canopy, some trees might have been left out from the actual count, leading to an undercounting of trees and an underestimation of the aboveground biomass (AGB). The photogrammetric dataset demonstrated a good tree height extraction accuracy and did not differ significantly from that determined by ground truthing (RMSE=2.59 m and 8.24%). The mean predicted height AGB from direct measurement was 24.76 tons ha^{-1}, higher than those obtained from single- and multi-set photogrammetry, 5.41 and 17.99 tons ha^{-1}, respectively. AGB and carbon sequestration estimated from photogrammetry were 72.66% of the ground truthing value. The accuracy of the photogrammetry results was acceptable and feasible for detecting individual tree heights, biomass, and carbon sequestration in the remnant forest. Overall, low-cost UAV could create a cost, time-efficient, and reasonably accurate local-scale forest inventory.

Keywords: Aerial photogrammetry, precision forestry, remnant forest, single tree segmentation, UAV

Abbreviations: aboveground biomass = AGB; canopy height model = CHM; closing and opening filter = COF; diameter at breast height = DBH; digital surface model = DSM; digital terrain model = DTM; Nakhon Chai Bawon = NCB; root mean squared error = RMSE; unmanned aerial vehicle = UAV; structure from motion = SfM; watershed segmentation = WS

INTRODUCTION

Urban forest remnants are remnants of forest ecosystems with environmental parameters and species compositions similar to historical natural forest benchmarks that are frequently altered by urbanization. (Kowarik and Moritz 2018). Urban forest remnants are biodiversity hotspots, region, or area that contains many different species of plants, animals, and other organisms, many of which are endemic or found nowhere else in the world. These areas are often under threat from human activities, such as habitat destruction or climate change, and conservation efforts are often focused on protecting these hotspots to preserve their unique biodiversity (Han et al. 2019). In urban areas where forests still exist, these small patches of forest can contain a high level of biodiversity, including various tree and animal species. This biodiversity is distributed relatively evenly among the different species present. In other words, even though these urban forest remnants may be small and fragmented, they can still play an important role in preserving and promoting biodiversity within urban environments. In urban areas where forests still exist, these small patches of forest can contain a high level of biodiversity, including various tree and animal species. This biodiversity is distributed relatively evenly among the different species present. In other words, even though these urban forest remnants may be small and fragmented, they can still play an important role in preserving and promoting biodiversity within urban environments. Additionally, such trees can supply regeneration seeds and modify the spatial dispersion and locations of future newly established tree cohorts (Herrera and Daniel 2009). An abundance of tree species creates a more diverse and complex ecosystem, which can provide habitat and resources that support the growth of late-successional species (Wu et al. 2022). A landscape's connectedness with the birds and other wildlife that need tree cover while traveling across the landscapes is ensured by the high value of remaining trees and forest areas. (Cadavid-Florez et al. 2020). Under suitable environmental conditions, the number of tree remnants positively impacts the recovery rates, density, basal area and size of trees being almost wholly recovered in less than 25 years (Doua-Bi et al. 2021). Unfortunately, not all populations of urban forest remnants are self-sustaining because of the impacts of urbanization and may result in the future extinction of native species.

Urban forest remnants play a significant role in accumulating biomass and carbon sequestrations in their structures (Liu and Li 2012). For calculating the amount of carbon that can be emitted or sequestered when urban forests are destroyed due to urbanization, tree biomass is crucial. Therefore, an accurate biomass estimation is critical to quantify the changes in biomass and carbon sequestration following the restoration of degraded forest landscapes (Mokria et al. 2018). Tree height is a fundamental measurement in forest inventory and a critical variable in assessing tree biomass and carbon sequestration (Larjavaara and Helene 2013). The measurement of tree height is a vital tree attribute used to calculate tree growth, biomass and carbon sequestration, providing crucial ecological information to decision-makers in urban forest management. Unfortunately, measuring tree height is often challenging and error-prone (Hunter et al. 2013). Tree heights can be measured using traditional techniques such as the thumb rule or trigonometric equipment, such as a clinometer, laser rangefinder and altimeter (Saliu et al. 2021). However, these methods are rarely contested. Over the years, the use of incredibly low-cost remote sensing methods in forest inventory, such as Unmanned Aerial Vehicle (UAV) platforms, has increased remarkably due to technological advancements and their cost-effectiveness (Lu et al. 2019). With the recent advances in UAV remote sensing technologies, the potential for semi-automatic estimation of accurate tree height has been realized (Zarco-Tejada et al. 2014; Panagiotidis 2017; Krause et al. 2019). Moreover, recent developments in remote sensing technologies for example LiDAR and digital photogrammetry using aerial images from low-cost UAVs, have opened new possibilities in estimating individual tree heights related to c and carbon sequestration in a forest. The use of UAV and photogrammetry in SE Asia forest inventory has only been briefly studied (Rinnamang et al. 2020; Usmadi and Pribadi 2021). Therefore, we explored the possibility of improving or replacing the traditional methods used in forest inventory that require manual field inventories over the whole forest area, as such methods are time-consuming, laborious and have scalability issues to build inventories at regional and larger scales. Our aims were as follows: (i) to determine the accuracy of individual tree detection and tree heights in urban forest remnants obtained from aerial photogrammetric from UAV relative to direct measurements; (ii) to estimate and compare the tree level AGB and carbon sequestration using direct measurements and aerial image photogrammetry techniques.

MATERIALS AND METHODS

Study site

The study was conducted in the Nakhon Chai Bawon (NCB) forest park (15°58'10" N and 100°13'25" E), located 250 km north of Bangkok, Thailand (Figure 1). Formerly a floodplain forest, the NCB area has been replaced by agricultural and urban land. The remnant forest was turned into an urban forest area of approximately 172.8 hectares, with the dominant tree species identified as *Dipterocarpus alatus* Roxb., forming the upper canopy. This tree species plays a dominant role in the ecology and economics of the riparian forests in Thailand (Kamyo and Asanok 2020). *D. alatus* is found in floodplain forests along a river basin in relatively flooded areas, including ravines along the rivers or deep-soil regions where the soil has a high water holding capacity (Asanok et al. 2017). Unfortunately, the decline has threatened it due to frequent flooding and illegal logging for timber and fuel. The floodplain forest is a critical forest type related to floral richness and is typically dominated by *Dipterocarpus* spp. (Majumdar and Badal 2016). Trisurat et al. (2011) reported that by 2100, future climate change would significantly change and threaten the distribution patterns of many dipterocarp species due to their ecological niche covering less than 1% of peninsular Thailand.

Field measurement

All *D. alatus* trees in the NCB were measured for their diameter at breast height (DBH) using a diameter tape (Lufkin Executive Thin line). The heights were also measured using a Vertex IV hypsometer, an instrument capable of measuring angles and distances using ultrasound techniques, with the tree heights calculated using the trigonometric principle (Hoglof 2017). Errors between 2-5% can be expected in the measured heights (Puliti et al. 2015). The coordinates of *D. alatus* trees were recorded using a Garmin ETREX Vista Cx handheld GPS (Garmin 2006). The small plot areas can be used for a regional ecosystem with many uniform-sized trees. For example, the 1,000 m^2 (100×10 m) plots should be used for rainforest communities with uniform stem sizes and even distributions of the stem to obtain a reasonable sample (>25) of the stand (Eyre et al. 2011). Therefore, in this work, five sample plots were included throughout the study area and were 1,600 m^2 (40×40 m) in size. These sample plots were used for data validation between tree height obtained from the ground truth and photogrammetry. All field measurements were collected from September to October 2021, at the same time the aerial images were taken.

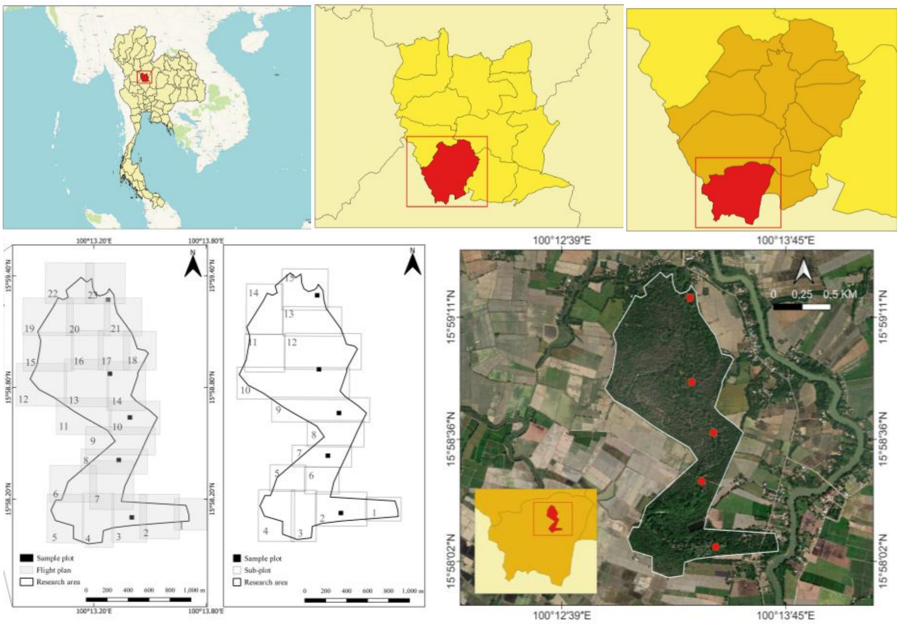

Figure 1. UAV flight-plans, study sub-plots and sample plots in the NCB Forest Park, Thailand

Data processing and tree height extraction

The aerial images were taken using a DJI Phantom 4 Pro multirotor UAV to capture RGB color images at a resolution of 20-megapixel with a field of view (FOV) of 8.8° (DJI 2016). The flight altitude was set at 200 m with a front and side overlap of 80 % and 70 %, respectively. The camera angle was set at 90° facing the ground. This method used the possibility of suitable image overlap during post-processing of the image to construct 3D maps (Ivosevic et al. 2017). Due to the UAV power supply limitation, we performed all twenty-one flights covering the study area using the same parameters. In total, 2,051 original images were processed to a point cloud using the structure from motion (SfM) technique, followed by densification leveraging multi-view stereo algorithms in the Pix4D software (Alonzo et al. 2018) to generate 2D and 3D maps. The images were processed and analyzed in the Pix4D Mapper 4.6.4 software to derive the Digital Surface Model (DSM) and Digital Terrain Model (DTM) using the SfM approach. We generated DTM and DSM from the total amount of aligned images. We initially reconstructed the DTM mesh using an automatic classification based on classified sparse point clouds of the ground, while DSM was based on the complete dense point cloud. The automatic classification was based on three parameters, i.e., maximum angle (deg), max distance (m) and cell size (m). We set the accuracy to high throughout the alignment step when the algorithm attempts to locate and match points between overlapping images. Tree height was obtained from the Canopy Height Model (CHM) using the vertical distance between the top of the canopy (DSM) and bare ground (DTM) (Holmgren and Eva 2019; Mot 2021) (Figure 2).

Due to extremely high tree density, the original orthophoto was manually separated into 15 sub-plots based on heterogeneous topography related to DTM data. Segmentation of individual tree crowns is complicated, particularly in broadleaf, mixed, or multi-layered forests (Ferraz et al. 2012). Therefore, the image was blurred and grayscaled, with binarization through closing and opening filter (COF), segmenting the smoothed canopy height model at each sub-plot, using watershed segmentation. Lastly, we used image moments to generate the canopy cover of each tree. It treats the gray-level image as a topographic surface, with the gray value of each pixel interpreted as an altitude value (Yang et al. 2020). The watershed segmentation (WS) algorithm is used on a single tree segmentation using Python to calculate the canopy coverage (Chen et al. 2006). The photogrammetric algorithm in this study was divided into 1) a single set of parameters used for the whole study area and 2) multiple sets of parameters, each sub-plot using a different parameter set (15 sub-plots in total). The tree heights were calculated from the raster layer, which used the crown's highest pixel values within a polygonal vector layer through the Zonal Statistics plugin in QGIS (Panagiotidis et al. 2017). The CHM was calculated by subtracting the DSM from the DTM using QGIS 3.22.

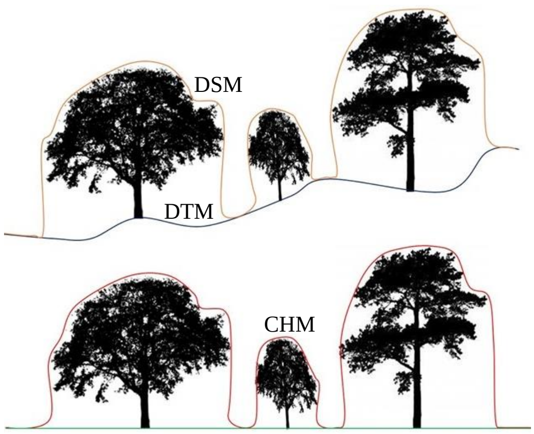

Figure 2. Digital Surface Model (DSM) and Digital Terrain Model (DTM) were used in CHM to calculate the total tree height

Estimation of AGB and carbon sequestration

The relationship between tree height obtained from the ground truth and photogrammetry was tested using linear regression analysis. After that, the constructed regression model was used to adjust each tree height derived from CHM. The adjusted height was then used as a prediction variable to calculate the DBH of each tree detected in orthophoto through a non-linear regression model between the tree height and DBH (Rinnamang et al. 2020). This model was constructed from the ground truthing of five sample plots. The AGB was calculated using the regression relation between individual tree height and DBH, which was estimated based on the allometric equations reported by Peawsa-ad and Viriyabuncha (2001), who developed the equations for *D. alatus* plantation (Table 1). Finally, AGB was converted into carbon sequestration using a conversion coefficient of 0.47 (Intergovernmental Panel on Climate Change 2006). The various steps and processes are elaborated in Figure 3.

Statistical analysis

We used linear regression to model the relationship between ground truthing and photogrammetry methods. R-squared was calculated as a metric for accuracy. The statistical t-test was used to compare tree heights from ground truthing and photogrammetry methods. Additionally, box-and-whisker plots were used to illustrate the variance for the ground truthing and photogrammetry estimated variables. The datasets to be validated were assessed by quantifying the total, systematic, and random errors, as well as the coefficient of determination (R2). We adopted the method recommended by Larjavaara and Helene (2013) and used systematic (bias) and random errors to differentiate between precision (lower random error) and accuracy (low systematic error). The total error was determined by calculating the root mean squared error (RMSE):

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum(t_{\mathrm{uav},i} - t_{\mathrm{ground},i})^2}$$

Where $t_{\mathrm{uav},i}$ is the estimated tree height and DBH of the ith tree from photogrammetry, $t_{\mathrm{ground},i}$ is the ground truthing of tree height and DBH of the ith tree, and n is the number of trees.

We quantified systematic error with the mean measurement error:

$$\mathrm{ErrMn} = \frac{1}{n}\sum(t_{\mathrm{uav},i} - t_{\mathrm{ground},i})$$

We quantified random error with the sample standard deviation of the measurement errors:

$$\mathrm{ErrSD} = \mathrm{SD}(t_{\mathrm{uav},i} - t_{\mathrm{ground},i}) = \sqrt{\frac{1}{n-1}\sum(t_{\mathrm{uav},i} - t_{\mathrm{ground},i} - \mathrm{ErrMn})^2}$$

Table 1. Equation of AGB of the various parts of a *D. alatus* tree (Peawsa-ad and Viriyabuncha 2001)

Part of the tree	Equation	R^2
Stem	0.018)DBH^2 Ht($^{1.0196}$	0.9963
Leaf	0.0064)DBH^2 Ht($^{0.7885}$	0.9142
Branch	0.001)DBH^2 Ht($^{1.1556}$	0.9785
Total	0.0207)DBH^2 Ht($^{1.0286}$	0.9951

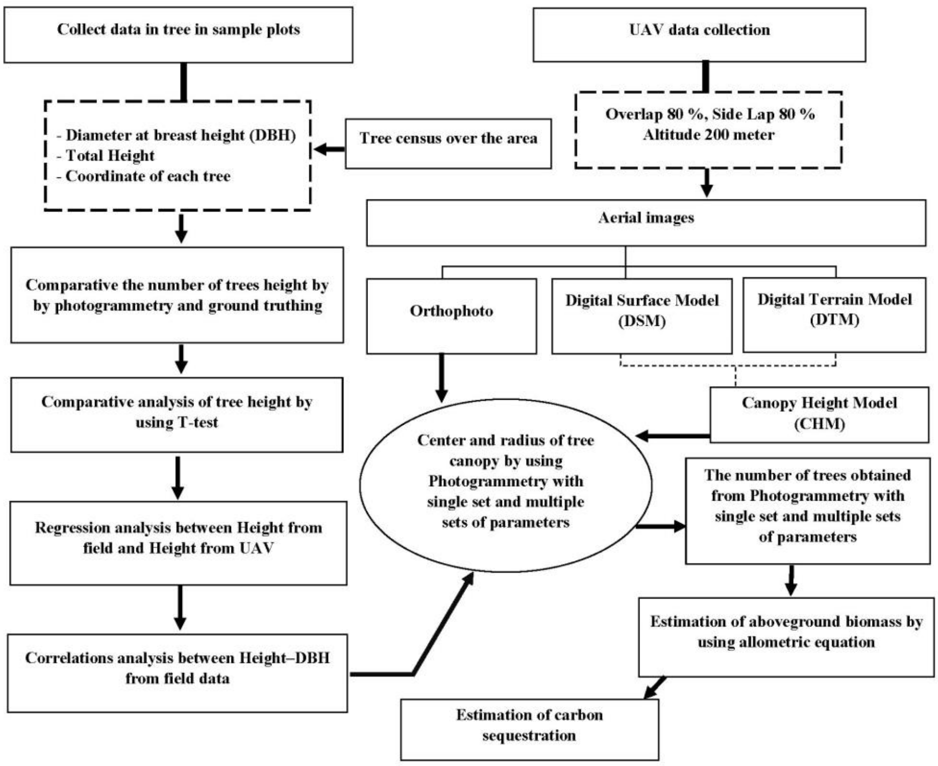

Figure 3. Workflow diagram of the present study

RESULTS AND DISCUSSION

Results

Validation with the ground truthing data

Through ground truthing, 1,115 *D. alatus* trees were identified and measured. The watershed segmentation (WS) algorithm was used in aerial photogrammetry to segment a single tree canopy based on a 3D point cloud (Figure 4). The results from data validation in five sample plots conveyed that at least 71% (85% of average) of *D. alatus* trees were automatically detected.

The direct measurement of tree height and DBH from five sample plots were used for data validation. Tree harvesting has been prohibited and not allowed in natural forests area of Thailand since 1989. Therefore, the direct height measurement of a tree was assumed to be the most accurate measurement possible within the framework of this study and was used as a control against which the photogrammetric dataset was compared. As shown in Table 2, relative to the direct measurement of tree height, the photogrammetric identification resulted in an RMSE of 2.59 m (8.24 %) and a systematic error of 0.17 m (0.54 %(, indicating an overestimation of tree heights and that the extraction accuracy of tree height was high. The random error was 2.64 m (8.39%). The estimated and measured tree heights showed a significant relationship with linear regression, as indicated by the R^2 values for the linear regression models (see Figure 5). On the other hand, DBH estimated from the photogrammetric datasets had a high RMSE of 20.17 cm (24.53%), as was the random error at 20.69 cm (25.16%). The correlation (R^2) between the DBH of the two datasets was 0.689. A better goodness of fit was obtained for the height compared to DBH (Figures 5 and 6).

Estimation of biomass and carbon sequestration

The relationship between tree height and DBH, as obtained through direct measurement, was fitted using a non-linear regression model (Rinnamang et al. 2020). The non-linear regression equation; $DBH=11.598e^{0.0587H}$ with a coefficient of determination of 0.6402 was used for the DBH prediction of each tree (see Figure 7). The adjusted height of individual trees was used to determine the DBH of all *D. alatus* trees in NCB. Then AGB was estimated per the parameters of the biomass equation, as shown in Table 1. The results from Table 3 indicate a distinct difference in AGB estimate based on a range of different parameters (15 plots) compared with a single set of parameters for the whole area. The AGB derived from a single- and multi-set of parameters were 5.41 and 17.99 ton ha^{-1}. These results were lesser than 24.76 ton ha^{-1} of AGB from the direct measurement. The total AGB and carbon sequestration of NCB from a multi-set of parameters photogrammetry was 3,109.50 tons and 1,461.25 tons, respectively, which was calculated to be 72.66% of ground truthing. The findings of this study suggest that the different number of trees identified through ground truth (1,115 trees) and photogrammetry techniques (490 trees from a multi-set and 74 trees from a single set) played an essential role in the observed differences in the AGB and carbon sequestration estimates.

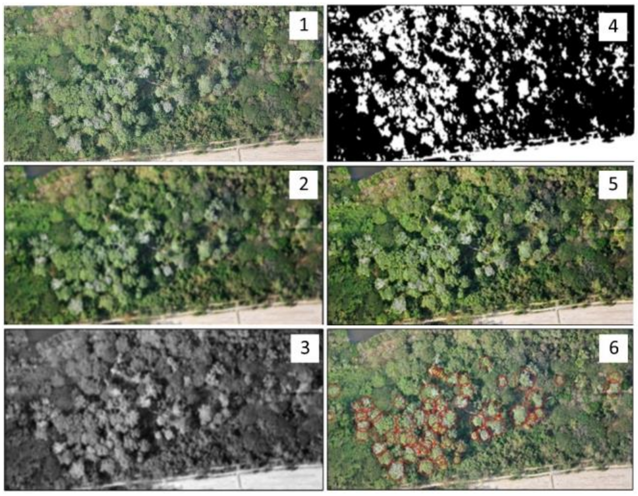

Figure 4. Chronology of single tree detection based on the watershed segmentation (WS) algorithm: (1) orthophoto, (2) blurred image, (3) grayscale image, (4) binarization with a closing and opening filter (COF), (5) watershed-segmentation and (6) image moment to identify the canopy cover of each tree

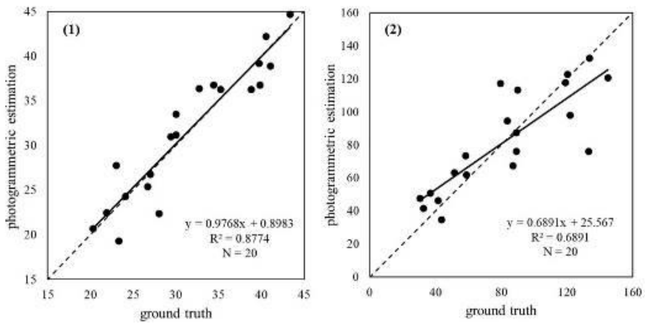

Figure 5. Results of the validation assessment comparing ground truth data and photogrammetric estimation of (1) height (m) and (2) DBH (cm). The dashed line represents the 1:1 line, and the solid line represents the fitted linear function. Parameters of the linear regression and coefficient of determination are given in each chart

Table 2. Tree estimated height and DBH using ground truthing and photogrammetric methods

Dataset comparison	Total error		Systematic error		Random error		Correlation	
	Value	(%)	Value	(%)	Value	(%)	R^2	P-value
H (m)	2.59	8.24	0.17	0.54	2.64	8.39	0.877	0.78
DBH (cm)	20.17	24.53	0.00	0.00	20.69	25.16	0.689	1.00

Table 3. AGB and carbon sequestration estimated from ground truthing and photogrammetric techniques (accuracy percentages are indicated in the parenthesis)

Source of AGB	Number of trees	AGB		Carbon sequestration)ton(
		ton ha^{-1}	Total (ton)	
Ground truthing	1,115	24.76	4,279.24	2,011.24
A single set of parameters	74 (6.64%)	5.41 (21.85%)	934.67 (21.84%)	439.30 (21.84%)
Multi-set of parameters	490 (43.95%)	17.99 (72.66%)	3,109.50 (72.66%)	1,461.25 (72.65%)

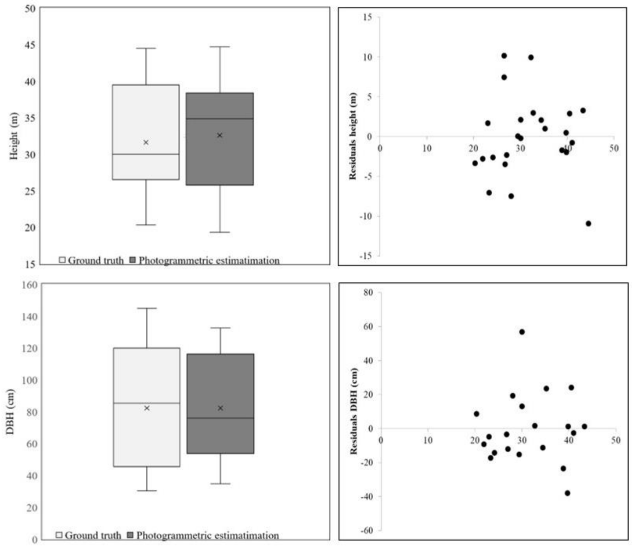

Figure 6. Box-and-whisker and residual plots of both the measured and estimated tree height and DBH

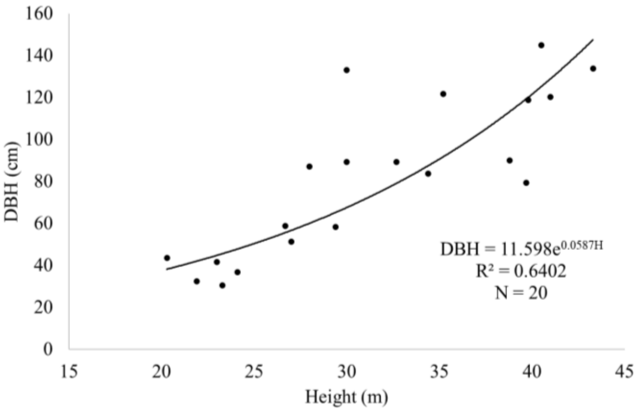

Figure 7. Non-linear regression between the tree height and DBH as obtained through ground truth data

Discussion

Point cloud and raster-derived tree heights obtained through various UAV technologies and photogrammetric techniques can be typically verified against ground-based observations. Photogrammetry combined with segmentation techniques can yield high accuracy based on the number of individuals sampled, which may be partly due to the use of high-resolution data (Holmgren and Eva 2019). From aerial

Figure 8. Significant factors responsible for the photogrammetry not being able to identify the trees: (A) suppressed or under a canopy and (B) continuous canopy in a dense growth of trees

images at a resolution of 3.27 cm, we generated DTM and DSM at resolutions of 27.00 cm and 5.54 cm, respectively. Zarco-Tejada et al. (2014) reported that when 30 cm pixel-per-pixel resolution imagery was used to create a DSM, the RMSE value thus obtained as a function of input pixel resolution was less than 15% but quickly deteriorated for input images with pixel resolutions below 35 cm. Unfortunately, from our results, half of the *D. alatus* trees remaining in this urban remnant forest could not be identified using photogrammetric detection due to trees with closed or suppressed canopies (see Figure 8). In this study, we observed three typical issues in detecting and identifying closed-canopy remnant forest, which includes 1) isolated trees in a single canopy, 2) trees growing in clusters within a continuous canopy and 3) unidentified suppressed trees. Furthermore, some other tree species were also identified due to the presence of faint objects or due to other species having a similar canopy. Regarding trees in forest plantations, Rinnamang et al. (2020) reported that more than 90% of trees were identified through photogrammetry techniques as they were planted at a given fixed spacing with distinct gaps in the canopy. However, they were unable to identify trees within double primary canopies, small replanted trees, or trees that were covered by nearby canopies of taller trees. Hence, forest with uniformly spaced trees offers a better level of tree detection than those in closed-canopy forests.

This study showed that the tree height estimated from the photogrammetric dataset in the urban forest remnants could be similar to ground truth data measured by an experienced forest technician as indicated by an RMSE of

2.59 m or 8.24%. However, a low accuracy in the estimated DBH from the photogrammetric dataset was observed (RMSE=20.17cm, 24.53%). This study agrees with Alonzo et al. (2018), who reported that the DBH of needle leaf trees could be estimated using the tree height with high precision, but such estimation was more challenging for broadleaf trees. The linear regression indicated that the tree height measured through ground truthing was comparable to the values estimated through photogrammetry (R^2=0.877). The result of RMSE from tree height estimation from this study was comparable with errors that may occur with a previous study found that the RMSE of estimated tree height was less than 20% (Zarco-Tejada et al. 2014; Panagiotidis et al. 2017). Height and DBH data sets tended to overestimate with a positive bias compared to the ground truth. The systemic error could be attributed to the total error in estimating tree height compared to DBH (0.54 vs. 0%). Random error is an important indicator when estimating DBH due to unknown biases resulting from uncertainty existing within the validation dataset. Tree height was derived from the CHM based on an evaluation of DSM and DTM, which modeled the top of the canopy. Therefore, tree height is usually based on the geometry of a forest structure and the spatial pattern of the targeted trees (Panagiotidis et al. 2017). Moreover, the direct measurement might also have errors due to uncertainty in determining the height due to the enormous size of *D. alatus* canopy in this study. It is essential to precisely determine the top of the tree canopy while estimating a tree's height. This is crucial when measuring trees with a large canopy. Precautions and potential errors caused by indistinguishable canopy should also be considered and necessary corrections should be made. According to the UNFCCC (2015), the error tolerance in measuring tree height while estimating the carbon stock is set at 1.0 m. Therefore, when direct measurements were used for validation, the tree heights estimated in this study were well within the error tolerance and data quality objective.

An allometric model was used to estimate AGB as a function of DBH and tree height, and it was assessed at both the tree and plot levels. The estimation of AGB is indicated by the overall precision of the estimated tree height and DBH through photogrammetry. According to the study by Yotthasarn and Petcharaburanin (2020), there is a strong positive correlation between total tree height and DBH of *D. alatus* trees (R^2=0.78). Therefore, inaccurate tree height measurements might result in inaccurate DBH and AGB estimates. On the other hand, Liang et al. (2018) suggested a higher, more decisive accuracy when DBH was used to estimate the biomass than tree height. Our results showed that 72.66% of the estimated AGB was comparable to that obtained through ground-truthing, even though only 43.95% of trees were identified. The trees that were missed or unidentified were too small to have an impact on the AGB estimate. Rinnamang et al. (2020) stated that the number of trees identified through photogrammetry and the respective tree height greatly affected the biomass estimation in *Tectona grandis* L.f. stands. It is still challenging to replace field-based measurements with UAV and photogrammetry methods, especially for tropical forest inventories, as the extraction and identification of individual trees from aerial images in dense canopy forests can be challenging. Additionally, automated algorithms that estimate tree height can have notable variations, particularly in structurally diverse and dense forest stands (Liang et al. 2018).

For the preservation of remnant forests, it is essential to understand the abundance of trees and AGB of critical species in such forests to help in the forest conservation plans. Acquiring high spatial and temporal resolution imagery through the low-cost UAV provides new opportunities to build a small-scale forest inventory to assess the precision of tree height measurements and AGB estimation. Thus, the height of critical tree species (*D. alatus*) was measured using aerial images taken by low-cost UAV and photogrammetry techniques. A comparison between reference ground truth measurement and photogrammetric estimation of tree parameters validated the workflow's implementation as reliable, effective, and could be used with sufficient precision. The outcome was considered satisfactory, with the tree height estimated using the photogrammetry method being accurate for all sample plots. This conclusion is based on a comparison with ground truthing data, which resulted in a low RMSE value. Nonetheless, some trees were missed due to a closed canopy resulting in an underestimation of the number of trees and AGB estimate.

This work can help preserve the urban remnant forests in a rapidly urbanizing world. In addition, we conclude that photogrammetry techniques using aerial images derived from low-cost UAV could be used in forests with accessibility issues. The replacement of direct tree inventories with UAV-based techniques is justified by a likely increase in the availability of such highly temporal datasets, reduced cost and time efficiency compared to field-based techniques, and the availability of technical professionals with the necessary experience. We recommended that the new tree inventorying approach be incorporated into the general practice when its benefits exceed those of the existing procedures. Finally, cost and usability are key factors that limit the value added to deploying UAV for forest inventories.

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