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Biomass and carbon storage of mangrove associate *Barringtonia acutangula* stand estimated using drone and non-destructive methods

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Abstract. *Pasha GAA, Chairul, Mukhtar E. 2026. Biomass and carbon storage of mangrove associate* Barringtonia acutangula *stand estimated using drone and non-destructive methods. Asian J For 10 (1): r100138. https://doi.org/10.13057/asianjfor/r100138.* Mangrove forests are among the largest carbon-storing forest ecosystems in the world, making them highly important in addressing climate change. However, the capacity for carbon uptake and storage within biomass varies considerably among species. Consequently, carbon storage across habitats is strongly influenced by dominant species and tree density. This study aims to analyze biomass and carbon storage in the stands of mangrove associate species, i.e. *Barringtonia acutangula* in Tangkas Lake, Jambi, Indonesia. A drone-based method and a non-destructive field survey were employed to collect data on mangrove vegetation. Drone was employed to generate Digital Elevation Model (DEM), Digital Terrain Model (DTM) and Canopy Height Model (CHM) to produce biomass and carbon estimate analyzed using formulas in R-studio. Biomass and carbon estimate from non-destructive field approaches were calculated using allometric equations by inputting DBH and tree height measured in the field. This data was also used to validate CHM and biomass and carbon calculated using drone-based method. The results show that the carbon storage of the *B. acutangula* stands obtained from the drone-based method and the non-destructive method are relatively similar. The mean biomass using drone-based accros transect was 66.425 tons/ha with the mean carbon storage was 31.219 tonC/ha, whereas the mean biomass estimation from the field survey resulted in 64.966 ton/ha with the mean carbon storage was 30.533 tonC/ha. Based on these results, *B. acutangula*-dominated stands in Tangkas Lake is included in the medium category implying its significant contribution in climate change mitigation. The findings of this study also suggest the potential application of drone-based methods in estimating above-ground biomass and carbon storage in freshwater mangrove ecosystem.

Keywords: AGB, *Barringtonia acutangula*, carbon storage, mangrove, photogrammetry

INTRODUCTION

Forests constitute a fundamental component of the global carbon cycle. Among them, mangrove forests exhibit exceptionally high carbon storage capacity (Jaikishun et al. 2017; Ramdhun and Appadoo 2020; Arnaud et al. 2023; Hilmi et al. 2024), sequestering approximately 10% of atmospheric carbon (Uddin et al. 2023) and storing up to four times more carbon than most terrestrial forest ecosystems (Adame et al. 2021). Their substantial carbon sequestration potential underscores the vital role of mangroves in global climate regulation (Azman et al. 2021). Accordingly, safeguarding mangrove ecosystems is essential for mitigating the impacts of global warming (Soeprobowati et al. 2024) and for informing management strategies related to forest carbon storage (Wirasatriya et al. 2022), which are pivotal for the success of conservation initiatives (Aabeyir et al. 2020).

Mangrove vegetation is broadly categorized into true mangroves and associate mangroves (Nabeelah et al. 2019). Associate mangrove species occur adjacent to or behind true mangrove zones and may grow in terrestrial margins or at the periphery of mangrove stands. While true mangrove species are typically found in coastal saline environments, several mangrove-associated species, such as *Barringtonia acutangula* (Lecythidaceae), occur in freshwater or low-salinity riparian systems (Tarigan et al. 2022). These species primarily thrive in drier, more stable environments (Rahim and Baderan 2019). This species frequently dominates riparian landscapes and coexists with a wide range of plant communities (Ananda et al. 2019). Its capacity to withstand substantial fluctuations in water levels (Sultana et al. 2019) positions it as a key ecological species in stabilizing freshwater and riparian environments (Dudhane et al. 2025). *Barringtonia acutangula* is a perennial, cluster-forming tree which can reach heights of 9-15 m, and is characterized by elongated leaves, fissured grey bark, pendulous red inflorescences, and elongated fruits (Sultana et al. 2019; Dewi et al. 2023). Ecologically, it plays an integral role in soil stabilization, nutrient cycling, and carbon sequestration by capturing atmospheric CO_2 and storing it in aboveground and belowground biomass as well as sediments (Kauffman et al. 2011). Although *B. acutangula* is known to support various ecological functions in riparian and freshwater ecosystems, information regarding its role in aboveground biomass accumulation and carbon storage remains limited.

Advances in remote sensing technology have enhanced the precision and efficiency of biomass carbon assessments (Zeybek et al. 2023). Unmanned Aerial Vehicles (UAV), also known as drones, are equipped with sophisticated imaging sensors (Zhang and Zhu 2023) and facilitate the acquisition of high-resolution Digital Surface Models (DSM) and Digital Terrain Models (DTM) (Grottoli et al. 2021), thereby reducing reliance on destructive sampling methods and improving biomass estimation accuracy (Wirasatriya et al. 2022). Nonetheless, field-based non-destructive measurements remain necessary to validate UAV-derived interpretations (Basyuni et al. 2023).

Tangkas Lake, located in Muaro Jambi District, Jambi Province, Indonesia, has an extent of 403.11 ha and has been developed as a community-managed ecotourism site since 2017. The distinctive topography of Lake Tangkas supports dense vegetation dominated by freshwater mangrove associate species, contributing to its ecological uniqueness. In Tangkas Lake, the area is dominated by *B. acutangula* which forms stands in freshwater mangrove ecosystem, which is ecologically different from coastal mangrove forests in general.

Despite their ecological importance, biomass and carbon storage of mangrove associate species in freshwater ecosystems remain less studied compared to true mangrove ecosystems, and no previous study has quantified aboveground biomass and carbon storage of *B. acutangula* using integrated UAV and non-destructive methods in Indonesia. Most existing research has focused either on conventional field-based allometric approaches or on UAV applications in coastal mangrove systems. The absence of integrated UAV-field biomass assessment for this species and ecosystem type creates a significant knowledge gap regarding the applicability of integrated UAV-ground survey methods for mangrove associate species such as *B. acutangula*.

Therefore, this study aimed to estimate the aboveground biomass (AGB) of *B. acutangula* stands by integrating UAV-based and non-destructive field. The UAV data were used to support spatial characterization of the stands rather than to develop or validate a predictive biomass model. These findings are intended to support evidence-based mangrove conservation, provide data on the amount of carbon storage in freshwater mangrove-associated species, and form the basis for carbon trading regulations.

MATERIALS AND METHODS

Study area and period

This study was conducted from August to October 2025 in Tangkas Lake, located geographycally at 1°28'42"S and 103°24'33"E and administratively in Tanjung Lanjut Village, Sekernan Sub-district, Muaro Jambi District, Jambi Province, Indonesia (Figure 1). Tangkas Lake is a freshwater basin formed by the accumulation of river water (Dewi et al. 2023). The study area has alluvial soil types, which are typical of riverine and freshwater swamp enviroments and is characterized by freshwater hydrological conditions with periodic fluctuations. Salinity levels are generally low to negligible. These environmental characteristics provide suitable conditions for the growth of *B. acutangula* and influence the distribution of vegetation biomass. The study site was predominantly occupied by *B. acutangula* (Lecythidaceae), which constitutes the principal species within the area (Sultana et al. 2019). In addition to the dominant species, several other plant taxa were recorded during the field survey, including *Syzygium* sp., *Combretum* sp., *Diospyros* sp., and *Memecylon edule*. These associated species contribute to the structural complexity and floristic diversity of the study area.

Research procedure

Transect method was applied to collect field data on mangrove carbon storage. This ground-based survey was complemented by an Unmanned Aerial Vehicle (UAV) assessment using a DJI Air 3S to estimate carbon storage from high-resolution aerial imagery using non-destructive approach. Two sampling stations (Figure 1) were established at different distances within the study area, each comprising ten sampling plots, yielding a total of twenty plots. The plots were positioned following the geomorphological structure of the lake, with transects arranged perpendicular to the lake margin and extending inland toward areas where vegetation was still present.

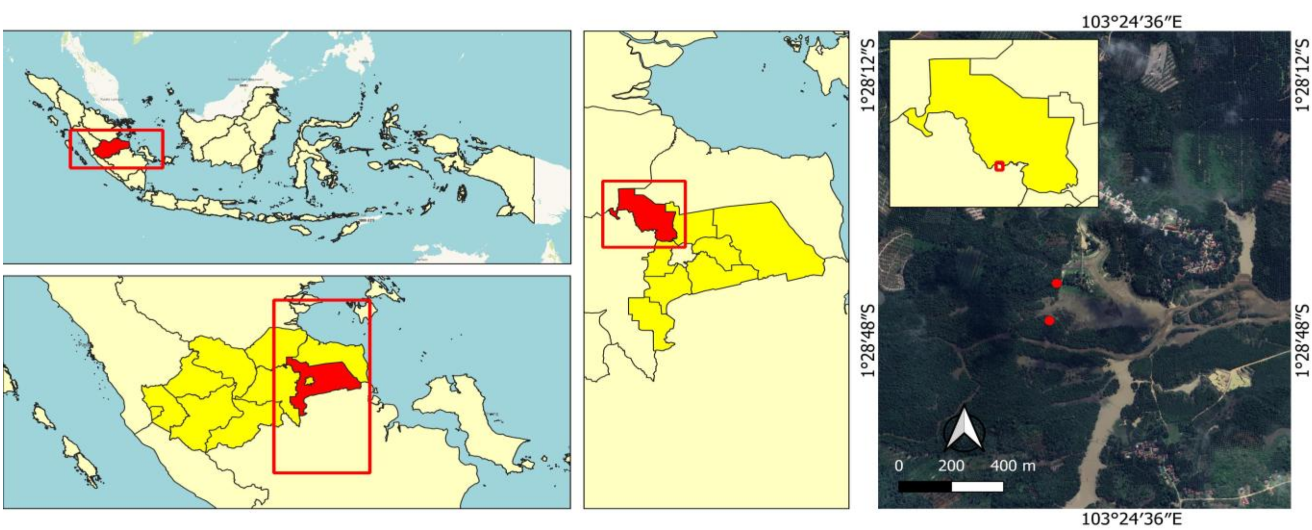


Figure 1. Map of the study area in Tangkas Lake, Muaro Jambi District, Jambi Province, Indonesia, showing two sampling stations

Field sampling

Mangrove surveys were conducted from 11 to 16 August 2025 at two sampling points within the study area. A purposive sampling approach was applied to select sampling locations within the study area. This method was chosen to ensure that plots were established in areas where *B. acutangula* was present, as the primary objective of this study was to estimate biomass and carbon stocks of this specific species. However, the use of purposive sampling can introduce bias, as samples are deliberately selected rather than randomly distributed. The results may not fully represent the heterogeneity of the entire study area and should be interpreted as applying primarily to the *B. acutangula* stands sampled. Two transects were established to provide spatial representation within the accessible area and to support field validation of UAV-acquired data. Transects were established using the belt transect method and placed within areas of dense vegetation. Each transect had size of 100 m × 10 m and ten sampling plot with size 10 m × 10 m each were created to collect biomass data for tree-level vegetation. Ten plots measuring 10 × 10 m were systematically arranged at 10 m intervals along each transect using purposive sampling. Field measurements followed the protocol of (Wirasatriya et al. 2022), within each transect, the parameters recorded included Diameter at Breast Height (DBH), measured using a standard diameter tape at 1.3 m above the ground surface, tree height measured with a Nikon Forestry instrument, and the total number of individual trees. A total of 229 trees were recorded during the field survey and 143 of them were *B. acutangula*. Only tree-level vegetation with a diameter greater than 10 cm was included in the analysis (Fachrul 2012). The DBH and tree height measured in the field were used for allometric biomass estimation and have the potential to validate Canopy Height Model (CHM), as well as for computing aboveground biomass (AGB) during UAV-based data processing. Although the total study area covers approximately 403 ha, the sampling design focused specifically on *B. acutangula* stands within selected locations. A total of 20 plots (0.2 ha) were considered sufficient to represent stand structure and biomass at the site level, given the use of purposive sampling and the results should be interpreted as representative of the sampled stands rather than the whole lake ecosystem.

UAV data acquisition and processing

A DJI Air 3S drone equipped with a 50-MP camera was used to capture high-resolution imagery across the 10-ha study area dominated by *B. acutangula* stands and mapped as a representative subset. All plots were located within this mapped area. Subsequently, UAV surveys were conducted following the same transect orientation to ensure spatial agreement between field measurements and canopy data obtained from remote sensing. The mapped area followed the vegetation distribution, including the distribution of *B. acutangula* along the lake shore. Aerial data acquisition was conducted using an aerial photogrammetry mapping technique, and the captured imagery was processed in Agisoft Metashape to generate topographic and geospatial products, including orthophotos and three-dimensional surface models. The drone was operated on 13 August 2025 at a flight altitude of 30 m, and produced 651 aerial photographs on transect 1 and 500 photographs on transect 2 with 75% overlap to ensure sufficient overlap to support accurate photogrammetric reconstruction. The resulting dataset accurately represents the condition of the mangrove stands at the time of the survey. In this study, Ground Control Points (GCP) were not used, and only direct georeferencing was employe. GCP were not installed due to limited accessibility and unstable, waterlogged substrate conditions within the study area. The absence GCP may result in reduced spatial accuracy of the UAV, with expected horizontal and vertical errors in the meter range. The impact of this limitation on the overall results is considered minimal since this study focused on estimating relative canopy height and assessing aboveground biomass (AGB) at the stand level. Therefore, the absence of GCP is recognized as a limitation for absolute positioning but is considered acceptable for the purposes of this study.

The UAV survey produced orthomosaic imagery, a Digital Elevation Model (DEM), and a Digital Terrain Model (DTM). The Canopy Height Model (CHM) was derived using the equation CHM = DEM - DTM, where the DEM represents the elevation of surface features (including vegetation) and the DTM represents the ground surface. The CHM was used to extract vegetation height and canopy structure information. The workflow included (i) UAV image acquisition, (ii) photogrammetric processing to generate orthomosaic and DEM, (iii) DTM extraction, and (iv) CHM derivation using raster calculations in QGIS. The CHM was then cropped to match the field plot size (100 × 10 m). Vegetation features were automatically detected from the CHM using a variable window filter algorithm (Popescu and Wynne 2004), with a minimum height threshold of 2 m. Detected tree points were visually verified using orthomosaic imagery in QGIS to remove non-mangrove objects. The final validated outputs were exported as shapefiles for further analysis. Aboveground biomass (AGB) estimation was carried out by deriving canopy height and canopy diameter from the CHM (Plowright 2017; Silva et al. 2022). The analysis utilized the AGB script developed by Jucker et al. (2016), while manual AGB calculations were conducted using allometric equations from Chave et al. (2014). Raster processing was performed using the raster package in RStudio (Allaire 2012).

Data analysis

Biomass and carbon estimation

The collected data were then analyzed to estimate the biomass of trees and saplings by measuring the Diameter at Breast Height (DBH), which was recorded in a tally sheet. Biomass per plot (10 × 10 m) is multiplied by 100 to get a ton/ha value of 0.01 ha, then averaged and added up per transect to get the overall total value. *Barringtonia acutangula* at the study site grows in a freshwater ecosystem in tropical lowlands with high rainfall and humidity-conditions more akin to the tropical moist forest category than to the dry or very wet categories. Therefore, aboveground biomass (AGB) was estimated using the allometric equation developed by Chave et al. (2014) for tropical trees:

$$AGB = 0.0673 \times (\rho D^2 H)^{0.976}$$

Where:
AGB: AboveGround Biomass (kg)
ρ: Wood density (g/cm^3) with value for *B. acutangula* is 0.52 referring to Global Wood Density Database by ICRAF (World Agroforestry Center)
D: Diameter at Breast Height (DBH) in cm
H: Tree height in meters (m)

For estimating tree carbon storage, the calculation was performed using the equation proposed by Hairiah and Rahayu (2007). A carbon fraction value of 0.47 was applied as a standard approximation of organic carbon content in biomass, which is widely used in carbon stock studies (Hairiah and Rahayu 2007; Intergovernmental Panel on Climate Change (IPCC) 2006). However, it should be noted that carbon fractions may vary among species and plant organs, and the use of a fixed value may introduce some degree of uncertainty in the estimation. Carbon storage estimation was estimated as follow:

$$Cb = Bo \times \%C \text{ organic}$$

Where:
Cb: The carbon content in biomass
Bo: Biomass (kg)
%C organic: The percentage value of organic carbon content (0.47)

Statistical analysis

Data tabulation used RMSE analysis, mean and SD (Standard Deviation), and minimum-maximum data. Data were tabulated in tables and figures. The analysis was descriptive, focusing on estimated error values, mean, standard deviation, and range to characterize biomass distribution.

RESULTS AND DISCUSSION

Number of trees estimated using UAV

The UAV survey conducted in the Tangkas Lake successfully generated high-resolution spatial data in the form of an orthophoto (Figure 2), processed using Agisoft Metashape software. The UAV data processing resulted in the production of an orthomosaic, a Digital Elevation Model (DEM), and a Digital Terrain Model (DTM). The orthomosaic provides detailed horizontal spatial information of the study area, while the DEM represents the elevation of surface features, including vegetation canopy and ground objects. In contrast, the DTM depicts the underlying terrain surface with vegetation and aboveground objects removed. Together, the DEM and DTM capture spatial variability in surface elevation and the three-dimensional structure of the landscape. Subsequently, a Canopy Height Model (CHM) was derived by calculating the difference between the DEM and DTM, enabling the estimation of vegetation canopy height and supporting further analyses of forest structure and aboveground biomass.

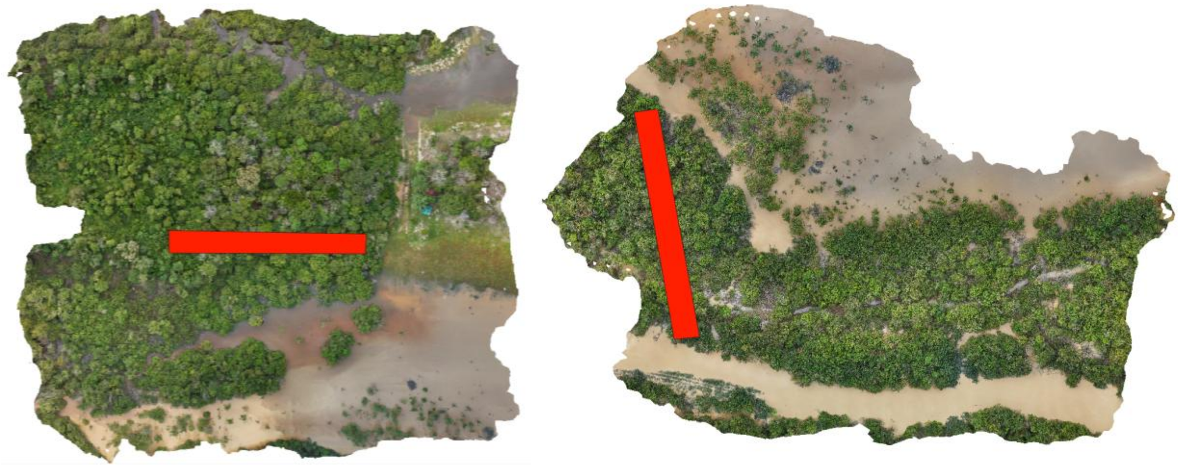
The CHM served as the primary dataset for estimating mangrove tree density, with the orthomosaic providing the visual backdrop for spatial interpretation. Tree detection and individual count estimation were performed automatically using the Treetop package (Silva et al. 2022) and the ForestTools package (Plowright 2017). Using these CHM-derived outputs, the estimated number of individuals and canopy height for trees within both plot locations were successfully obtained.

Based on the analytical results generated using *R*-Studio, the objects marked with red dots (Figure 3) represent the distribution of individual tree canopies (treetops). From this output, the estimated number of individuals within the two plots was obtained. Transect 1 contained 122 individuals, whereas transect 2 contained 119 individuals (Table 1). These data also provide several height-related parameters, including the maximum tree height (Hmax), mean tree height (Hmean), minimum tree height (Hmin), and median tree height (Hmedian), which collectively describe the vertical structure of the mangrove stand. According to the height threshold applied in *R*-Studio, only trees with a canopy height of ≥2 m were detected (Pohan et al. 2021). Consequently, individuals with a height below 2 m were not included in the automated tree-counting process. Several methodological limitations, such as the application of a minimum height threshold (≥2 m), exclude smaller individuals, as only the stand-level tree species were observed. Species identification based on UAV imagery may involve some degree of misclassification due to canopy similarities between species. Despite these limitations, this approach remains suitable for characterizing stand-level biomass of *B. acutangula*.

Tree heights ranged from 2.9 to 9.0 m, with mean heights of 6.8 m and 4.7 m in transects 1 and 2, respectively (Table 1). The median tree height was 7 m in transect one and 4.5 m in transect two. Generally, mangrove vegetation height ranges between 9-15 m, depending on species and habitat conditions (Sultana et al. 2019; Dewi et al. 2023). The number of individuals showed no substantial difference in stand density between sites, with 122 individuals recorded in transect one and 119 individuals in transect two. This indicates relatively high stand density within both community structures. Mangrove density is influenced by the number of individuals within each plot (Purnama et al. 2020) and tree diameter (Hikmatyar et al. 2015), thus providing important information on stand structure and biomass characteristics of the area.

Mangrove identification based on UAV

Identification of mangrove species using UAV imagery remains challenging, as automatic classification is often hindered by the high physiological (affecting color and tone) and morphological variability among species. To validate mangrove features derived from drone surveys, advanced analytical tools are required for species-level discrimination (Kamal and Haris 2014). After the treetop and vegetation point data obtained from the height were generated, manual verification was carried out to determine the species identity from field observations (botanical identification) and then linked to the treetops detected by the UAV, while individuals that could not be identified with certainty were recorded as “other species” (Figure 4). Red points that did not correspond to mangrove vegetation were removed, and the final validated dataset was then exported as a shapefile (SHP) for subsequent analysis.



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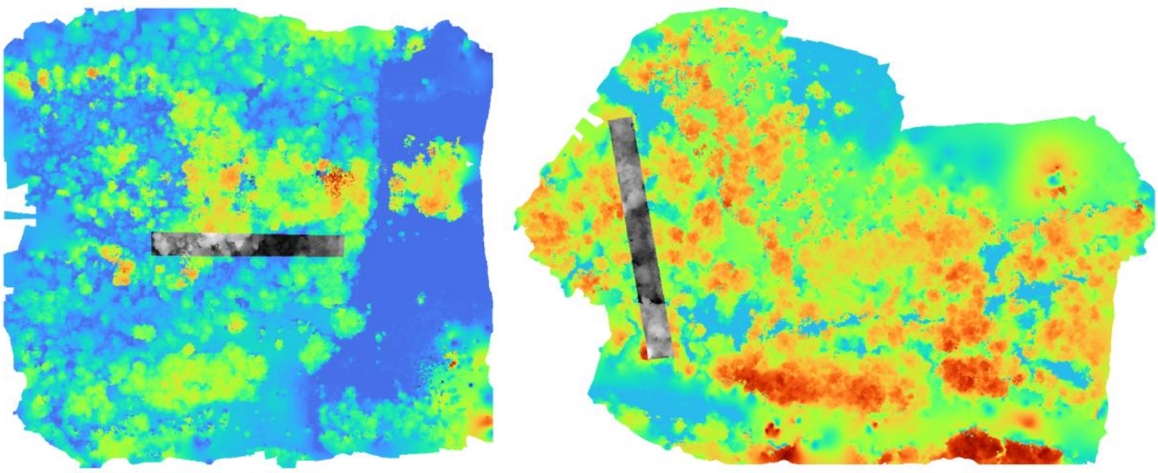

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Figure 2. The visual representation of the UAV-derived datasets. A. The orthomosaic, and B, The CHM, which was generated by integrating the DTM and DEM for the study area

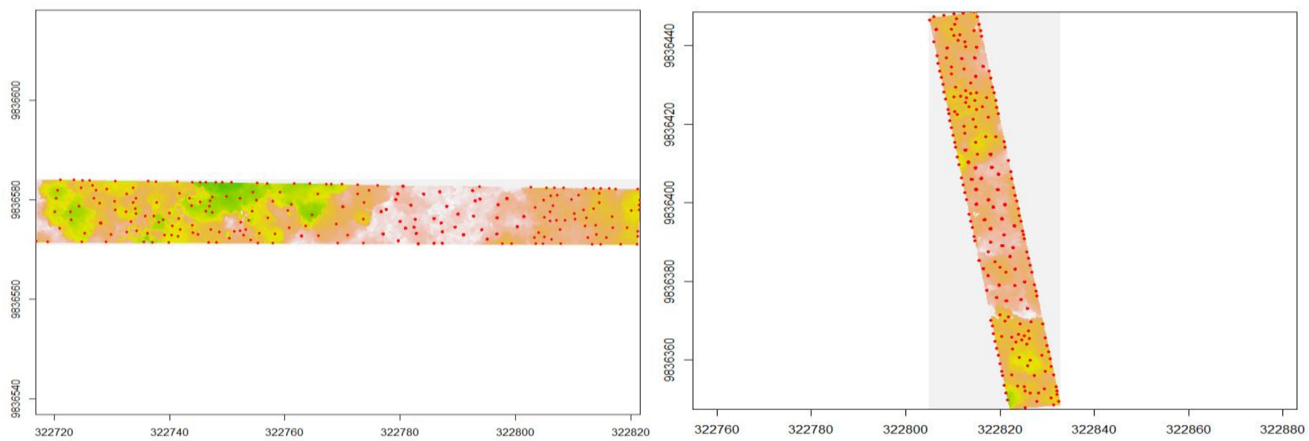

Figure 3. Distribution of individual trees (treetops) in both sampling stations

Based on the estimation results using a UAV approach, the total number of trees was 241 individuals on both transects (Table 1). In transect one, 122 individuals were recorded, of which 60 individuals were identified as *B. acutangula*, while 62 individuals were classified as others (Table 2). In transect two, 119 individuals were recorded, of which *B. acutangula* consisted of 97 individuals while 22 individuals as others. Meanwhile, field validation conducted on two transects recorded 229 individuals, of which 143 individuals were *B. acutangula* or equivalent of stand density of 715 trees/ha.

This result corresponds to a detection accuracy of approximately 95%, with an error rate of about 5%, indicating that the UAV method provides a reliable estimation of tree counts at the stand level. Comparison of the two results shows that the estimation of individual tree numbers using the UAV method produces values relatively comparable to direct measurements using non-destructive field methods. This indicates that the use of the UAV system is capable of providing vegetation inventory information, including tree counts, with a relatively high level of accuracy. According to Jones et al. (2020), orthomosaic data captured by UAVs can also be used accurately to identify and count individual trees in mangrove ecosystems. High-quality, processed images allow for more precise tree counts, allowing for estimates of freshwater mangrove-associated vegetation biomass with relatively low standard errors.

The results also indicate that *B. acutangula* was the most common species across both sampling areas. Although species identification can be conducted using UAV-based surveys, detailed and fully automated species-level classification remains limited (Zhang and Zhu 2023), and accuracy is strongly influenced by the technological capabilities of the drone and the resolution of the imagery.

Biomass and carbon storage estimated using non-destructive method

The biomass and carbon storage of an individual plant are primarily determined by three key components: stem diameter, tree height, and wood density. The results of this study demonstrate that, in addition to stem diameter, tree height and wood density also contribute to increasing biomass and carbon storage. Nevertheless, stem diameter remains the most influential determinant (Hikmatyar et al. 2015), as trees with larger diameters generally possess greater wood volume and mass (Sulistyorini et al. 2020), thereby making a substantial contribution to total biomass and carbon stock. Figure 5.A shows the regression between DBH and biomass with an R^2 value of 0.904 with a correlation of 0.951, indicating a very strong positive correlation between tree DBH and biomass. Tree height also showed a significant positive correlation with biomass with an R^2 value 0.498 with a correlation value of 0.706 (Figure 5.B). These results confirm that variations in *B. acutangula* biomass at the study site are primarily influenced by tree diameter and height, as also reported in previous studies (Hikmatyar et al. 2015; Sulistyorini et al. 2020).

The analysis of biomass and carbon storage per plot in the mangrove area of Lake Tangkas shows clear differences between the first and second transects (Figure 6). In the first transect, the highest recorded biomass was 9.603 tons/ha, whereas the second transect reached a maximum biomass of 27.171 tons/ha (Table 3). This pattern reflects the influence of tree height and diameter on biomass accumulation. Trees with larger diameters generally exhibit higher biomass values (Purnamasari et al. 2020). The total height of the plots on transect one is 355.8 m with a diameter of 1199.5 cm, while on transect two the total height of all plots is 434.9 m with a diameter of 1743.4 cm. The total biomass estimated for *B. acutangula* in the first transect was 62.178 tons/ha, while the second transect contained 67.754 tons/ha (Table 3). Based on field survey data, the total number of *B. acutangula* individuals recorded was 143 trees on a plot area of 0.2 ha, resulting in a stand density of 715 trees/ha.

Variability in biomass and carbon storage was evaluated using Standard Deviation (SD) (Table 3). In transect 1, the mean biomass per plot was 6.22±1.89, while the mean carbon storage was 2.92±0.89, indicating relatively low to moderate variability around the mean values. In contrast, transect 2 showed a mean biomass per plot of 6.77±7.65 and a mean carbon storage of 3.18±3.59, which shows a very high level of variability in biomass and carbon storage compared to transect 1. The markedly higher standard deviation in transect 2 suggests pronounced heterogeneity in mangrove stand structure. This indicates variability in tree biomass across each transect, reflecting differences in diameter and height among individuals. Conversely, the lower variability observed in transect 1 indicates a more homogeneous vegetation structure, resulting in a more uniform distribution of biomass and carbon storage. These patterns highlight the influence of environmental heterogeneity in shaping spatial variation of biomass and carbon storage across transects. The total carbon storage estimates obtained from each observation route have relatively similar values.

Table 1. The number and height of trees in each transect, along with the estimated biomass value of the UAV

Transect 1		Transect 2	
Number of individuals	122	Number of individuals	119
H_{max}	9 m	H_{max}	8.8 m
H_{mean}	6.8 m	H_{mean}	4.7 m
H_{min}	4.2 m	H_{min}	2.9 m
H_{median}	7 m	H_{median}	4.5 m

Table 2. Species composition and number of individuals in the study area

Location	Species	Number of individuals	Total
Transect 1	*Barringtonia acutangula*	60	122
	Other species	62	
Transect 2	*Barringtonia acutangula*	97	119
	Other species	22	

Table 3. Total carbon storage based on non-destructive analysis

Location	Height (m)	Diameter (cm)	Biomass ton/ha	Means ± SD	Carbon ton/ha	Means ± SD
Transect 1	355.8	1199.5	62.178	6.22±1.89	29.223	2.92±0.89
Transect 2	434.9	1743.4	67.754	6.77±7.65	31.844	3.18±3.59
Total	790.7	2942.9				

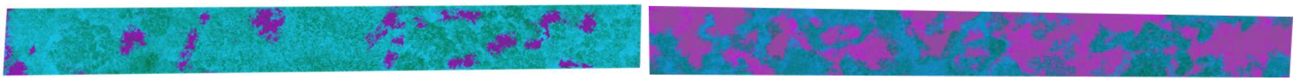

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Figure 4. Identification of mangrove species at the two study sites: A. Transect 1, and B. Transect 2

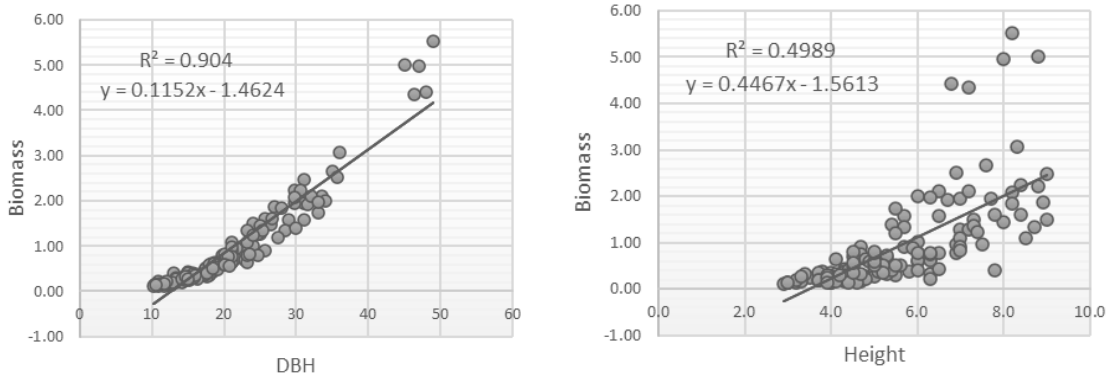

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Figure 5. Regression relationship between aboveground biomass and dimensional variables of *Barringtonia acutangula*. A. DBH and B. Height

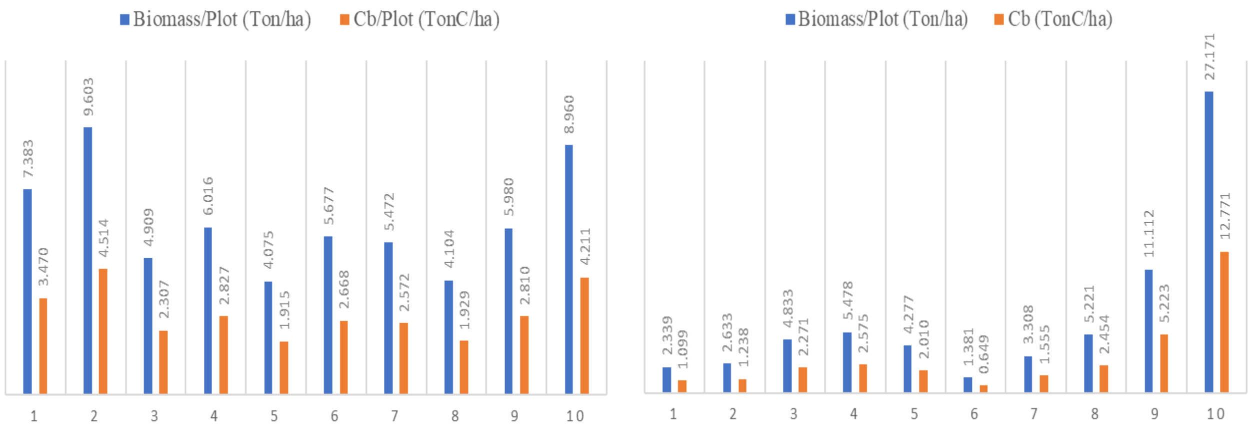

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Figure 6. Histogram of biomass and carbon storage *B. acutangula* per plot: A. Transect 1, and B. Transect 2

Biomass and carbon storage of *Barringtonia acutangula* estimated using UAV

Biomass within the plots at both sites was estimated after generating the CHM using R-Studio. Above-ground biomass (AGB) was calculated based on predicted tree height and canopy diameter extracted from the CHM data. Biomass estimation in this study was conducted exclusively for *B. acutangula* individuals. The inclusion of other individuals was intended to describe general stand composition, but these were not included in biomass calculations. The biomass in transect one was 63.750 tons/ha, while transect two contained 69.100 tons/ha (Table 4). These biomass values were influenced by the number of individuals and the canopy width within each transect.

Table 4. Aboveground biomass estimated using UAV

Transect 1		Transect 2		Mean
Biomass	63.750 ton/ha	Biomass	69.100 ton/ha	66.425 ton/ha
Carbon Storage	29.962 C/ha	Carbon Storage	32.477 C/ha	31.219 tonC/ha

Biomass accumulation is also strongly affected by trunk diameter (Hikmatyar et al. 2015), as trees with larger diameters generally exhibit higher biomass (Adinugroho and Sidiasa 2006). This finding is consistent with Harapan et al. (2021), who reported that UAV-based aboveground biomass estimation produced individual tree numbers that were comparable to field measurement data.

Tangkas Lake had relatively freshwater mangrove stands and contributes to the high biomass accumulation and carbon stocks. As shown in Table 1, the freshwater mangrove ecosystem in the Tangkas Lake area exhibits relatively high biomass and carbon stock potential. Based on UAV-based analysis, the mean biomass accros the transects was 66.425 tons/ha with the mean carbon storage was 31.219 tonC/ha (Table 4). Meanwhile, estimates obtained through direct field measurements using non-destructive methods showed slightly lower values, whereas the mean biomass estimation from the field survey resulted in 64.966 ton/ha with the mean carbon storage was 30.533 tonC/ha (Table 3). The comparison between UAV-based and field-based biomass estimation shows a low average difference and relatively small error, the RMSE value is around 0.1459, which indicates that the two methods have a very small difference so that they can be used as a non-destructive approach in estimating vegetation biomass in Tangkas Lake. The difference between the two methods was relatively small, indicating consistency and agreement between the remote sensing-based approach and the field survey.

Discussion

The comparison of carbon estimates obtained from the two methods: i.e. direct field measurements and drone-based analysis (Tables 1 and 3) shows that the results are relatively similar (Harapan et al. 2021). UAV surveys can produce accurate estimates across large forested areas, with total carbon values that closely match those derived from ground-based assessments. The high spatial resolution of drone imagery, which can reach below 1 cm, further enhances data precision. Meanwhile, direct field measurements provide very high accuracy because biomass values are derived from allometric equations applied to tree measurements collected in situ (Dinilhuda et al. 2020).

The *B. acutangula*-dominated stands within the sampled freshwater mangrove ecosystem in Tangkas Lake fall into the medium carbon category. The classification of carbon storage in the form of aboveground biomass (AGB) is based on Badan Perencanaan Pembangunan Nasional (Bappenas 2010) which groups them into three categories, namely low category if the value of carbon storage is <35 tons/ha, medium category if the value of carbon storage is 35-100 tons/ha, and high category if the value of carbon storage is >100 tons/ha. In this study, the carbon storage values obtained from both methods were comparable, indicating consistent biomass estimation. Given that Tangkas Lake has a medium carbon storage level, this demonstrates the significant role of the study area in storing carbon storage. However, this study is subject to spatial limitations, as field sampling was conducted using two transects, which represents only a small portion of the total Tangkas Lake area (±403 ha). Consequently, the estimated aboveground biomass and carbon storage reflect *B. acutangula*-dominated stands within the sampled area rather than the entire lake ecosystem.

In conclusion, estimates of *B. acutangula* biomass and carbon storage obtained using drone-based and non-destructive field methods show relatively similar values. The sampled stands showed medium carbon storage with comparable results between UAV and field methods. The AGB drone can provide values with a difference of 2.9 tons/ha from direct field measurements. The small discrepancy between the two methods indicates that the drone-based approach has a level of accuracy comparable to the field survey. These results underscore the need for the development of additional ecological variables and drone-based temporal analysis to strengthen the understanding of the ecological factors influencing biomass and carbon distribution in freshwater mangroves. These findings are limited to the sampled stands and may not represent the entire Tangkas Lake ecosystem. To characterize carbon storage at the lake-wide scale, future studies should expand field sampling and UAV coverage to encompass a wider range of vegetation types and spatial heterogeneity across the lake.

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