

High-resolution Unmanned Aerial Vehicles (UAV) imagery for estimating above and below-ground biomass in mangroves of Rembang, Central Java, Indonesia

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Abstract. Iryanthony SB, Wirasatriya A, Pribadi R, Purnomo PW, Muchtar E, Basyuni M, Wijayanto D. 2025. High-resolution Unmanned Aerial Vehicles (UAV) imagery for estimating above and below-ground biomass in mangroves of Rembang, Central Java, Indonesia. *Biodiversitas* 26: 2065-2078. Mangrove ecosystems are essential for climate change mitigation. The blue-carbon ecosystems in Pasar Banggi, Rembang, Central Java, Indonesia, sequester carbon and reduce emissions. The Essential Ecosystem Area in Pasar Banggi, Rembang, encompasses 36 hectares along a 2.7 km stretch and can support two flights at an altitude of 120 meters Above Ground Level (AGL). This site assesses Unmanned Aerial Vehicles (UAV) methodologies for Above-Ground Biomass (AGB) using a Phantom 4 Pro Obsidian true color sensor with a resolution of 20 MP. UAV offer remarkable accuracy and resolution of 4.1 cm per pixel. This study evaluates the volume of AGB and the carbon sequestered in mangroves utilizing aerial footage obtained from UAV and accurate Global Navigation Satellite System (GNSS) data. The study creates precise digital surface models and digital terrain models to determine the mangrove canopy elevations. The horizontal accuracy (CE90) is approximately 0.0201 m, whereas the vertical accuracy (LE90) is around 0.0249 m. The canopy heights are 1-6 m along the beach and 1-14 m further inland. Applying an allometric equation specified for Southeast and East Asia region yields an AGB ranges from 6 to 317 mg/ha. AGB is then converted into Below-Ground Biomass (BGB) through a ratio, producing total biomass as the aggregate of AGB and BGB. BGB ranges from 2 to 123 mg/ha with total biomass can attain levels of up to 440 mg/ha. In this site, *Rhizophora mucronata*, *R. apiculata*, and *R. stylosa* constitute most of the total area covering biomass, 38%, 27%, and 9%, respectively, demonstrating their significance in carbon sequestration. The high accuracy of AGB estimation with root mean square error of 8.95 mg/ha demonstrates the considerable efficiency of combining UAV and GNSS technologies in improving the precision of biomass estimation for carbon stock assessments.

Keywords: AGB, drone, Loray's, mangrove, photogrammetry

INTRODUCTION

The increasing greenhouse gas concentrations drive global warming (Coe et al. 2021; Nunes 2023). The post-industrial revolution led to a substantial rise in carbon dioxide (CO₂) concentrations (Graven et al. 2020; Cecilia et al. 2021; Shah et al. 2023), and reducing these levels is crucial to mitigate the impacts of global warming (Coe et al. 2021; Shah et al. 2023). Mangroves, as blue carbon ecosystems, play a pivotal role in carbon sequestration, storing 10% of atmospheric CO₂ (Arnaud et al. 2023; Uddin et al. 2023), far more than terrestrial forests (Adame et al. 2021). Therefore, their preservation is critical to mitigate the impacts of global warming (Chatting et al.

2022; Soeprobowati et al. 2024).

Precise and comprehensive information on carbon storage in mangrove forest is essential for successful conservation initiatives (Tang et al. 2018; Aabeyir et al. 2020; Wirasatriya et al. 2022). Indonesia possesses almost 20% of the global mangrove area (approximately 2.7 million hectares; Budiadi et al. 2023; Miller and Tonoto 2023; Sasmito et al. 2023), distributed across 257 areas. Existing biomass estimation methods predominantly utilize low-resolution satellite data with a resolution of >10 m (Amuyou et al. 2022; Ahmad et al. 2023; Chen et al. 2023). While these methods are appropriate for large areas, the limited resolution constrains their application (Amuyou et al. 2022; Ahmad et al. 2023). Remote sensing satellites

enable a more realistic and feasible approach for large-scale regions (Pham et al. 2020; Amuyou et al. 2022; Ahmad et al. 2023).

Rapid advances in remote sensing technology have transformed mapping techniques (Zeybek et al. 2023), especially drones and Uncrewed Aerial Vehicles (UAV) equipped with powerful sensors (Chi et al. 2023; Zhang and Zhu 2023). Drones provide immediate, high-quality information with centimeter precision, making them a productive substitute for generating the Digital Surface Models (DSMs) (Aiman et al. 2018; Grottoli et al. 2021) essential for biomass estimation (Wirasatriya et al. 2022; Bazrafkan et al. 2023; Qiu et al. 2023). However, due to the limitation of remote sensing techniques, we focus on the AGB mangrove that also has successfully applied by Wirasatriya et al. (2022), Basyuni et al. (2023, 2025a, b).

Pasar Banggi Village, in Rembang District, Central Java, Indonesia (Figure 1), has a dense mangrove environment, with high species variety, and significant ecological importance (Soeprbowati et al. 2024). While the mangrove ecosystem in Rembang District has been diminished due to land conversion, industry, tourism, and fish-ponds (Soeprbowati et al. 2024), mangrove restoration efforts have been successful in Pasar Banggi. In 1960, this area covered only about 3 hectares, but restoration by local communities and the government in 1973, 1988, and 2000 successfully expanded it to 60 hectares (Muqorrobin et al. 2013). Recently, the Governor of Central Java issued Decree No. 552.52/31 of 2020, officially designating the Pasar Banggi mangrove ecosystem as an essential ecosystem area in Central Java Province. This designation highlights its ecological, economic, and socio-cultural significance for the local community, emphasizing the need for its preservation.

As one of the remaining mangrove ecosystems along the northern coast of Java, the mangrove in Pasar Banggi is crucial to the blue carbon ecosystem (Kartadikaria et al. 2015; Wirasatriya et al. 2022). However, the recent estimate of the areal size of mangroves in Pasar Banggi is worrying, with only about 36 hectares remaining (Figure 1). This reduction implies that mangrove destruction has occurred in Pasar Banggi, and protecting the area's remaining restored mangroves is crucial. The detailed measurement of the carbon stored in the mangrove biomass is an important factor for mangrove protection in Pasar Banggi. Previously, Soeprbowati et al. (2024) estimated the Pasar Banggi mangrove ecosystem's total carbon stock potential at 0.02×10^6 mgC. However, their estimation method was based solely on in-situ measurement, lacking detailed investigation into the spatial distribution of mangrove carbon biomass. The current study is the first to provide accurate above and Below-Ground Biomass (BGB) mapping of mangroves by combining drone aerial images with Global Navigation Satellite System (GNSS) technology (Mao et al. 2021; Wirasatriya et al. 2022; Qiu et al. 2023), providing a foundation for carbon evaluation of mangroves in Rembang's coastal regions, essential for sustaining the blue carbon ecosystem.

MATERIALS AND METHODS

Study area

This research is conducted at the mangrove restoration sites in the villages of Tireman and Pasar Banggi, Rembang District, Central Java, Indonesia (Figure 1). The research area covers over 36 hectares, comprising one of the few remaining substantial mangrove habitats in the region. Intensive shrimp and salt ponds dominate the local area. Industrial operations and a steam power station are located further inland to the south. The mangrove restoration initiatives have effectively transformed the ecosystem into a rich and varied community with five unique species (Soeprbowati et al. 2024). The species encompassed in this group are *Avicennia marina*, *Excoecaria agallocha*, *Rhizophora apiculata*, *R. mucronata*, *R. stylosa*, and *Sonneratia* (Rahmat et al. 2022; Mustofa et al. 2023). *Rhizophora apiculata* and *R. mucronata* dominate the restoration landscape, reflecting successful planting efforts. The spatial distribution of these species highlights the established zonation patterns commonly found in tropical mangrove habitats.

Salt ponds predominate in the Tireman and Pasar Banggi regions (Figure 1). The Pasar Banggi community participates in fishing and salt cultivation throughout the summer. A prominent shrimp pond distinguishes Tireman from Pasar Banggi. Erosion and intense shrimp pond development have compromised the mangroves in Tireman. In addition, the restoration efforts are less vigorous than those in Pasar Banggi. In Tireman, several regions display deceased mangroves adjacent to shrimp ponds. The Pasar Banggi population excels at mangrove management, although the intensive salt ponds are the primary commodity. This explains why mangrove tourism in Pasar Banggi is more developed than in Tireman. Pasar Banggi has been designated as an Essential Ecosystem Area.

Data from the BPS (2024) indicates that Rembang District experiences a tropical climate characterized by a wet season lasting roughly four to five months annually. In 2023, the peak rainfall was documented in December, averaging 229 mm. The Gunem District recorded the greatest yearly precipitation, totaling 1,240 mm throughout 85 wet days. Rembang District is mostly characterized by lowland topography, with heights varying from 0 to 900 meters above sea level. The coastline of Rembang District measures around 63 km, but an alternative source indicates a figure of 51.5 km.

UAV photogrammetry

High-resolution photogrammetry data was collected utilizing the DJI P4 Pro Obsidian drone, fitted with a 20 MP camera, to scan the entire 45-hectare research area. The Structure from Motion (SfM) photogrammetry method facilitated data collection, producing orthophotos with a ground resolution of 4.1 cm/pixel and a Digital Surface Model (DSM) of 16.4 cm/pixel (Alganci et al. 2018). The drone ascended to an altitude of 120 m, capturing a total of 452 aerial photographs with 80% overlapping images on 2 March 2024. Thus, it represents the mangrove condition in the rainy season. The orthophotos and DSM were created

using a mosaic process on raw aerial photos. This process began with photo alignment, followed by the input of

Ground Control Points (GCPs), and then the construction of a dense cloud, mesh, and texture.

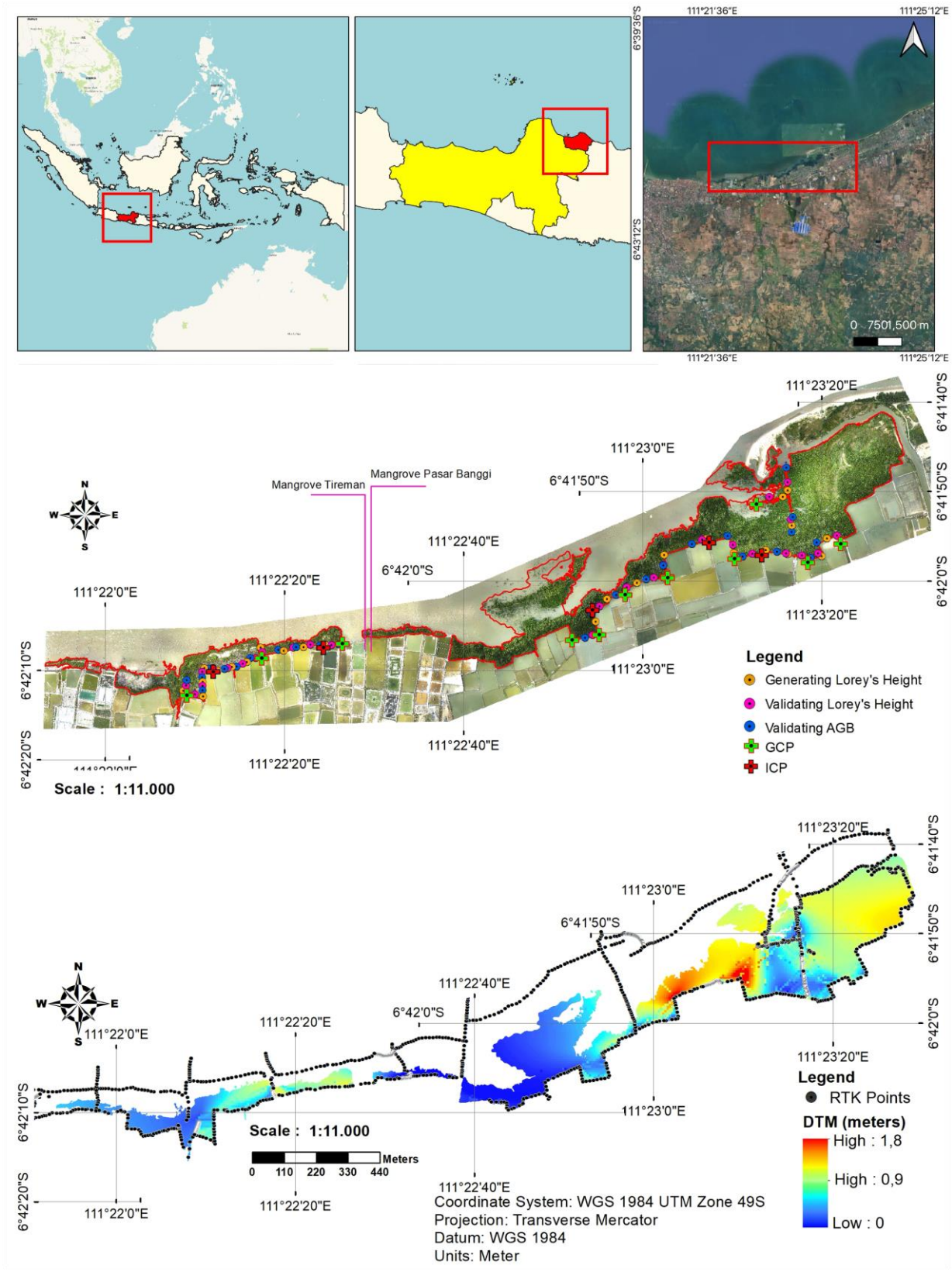


Figure 1. Research area. This is an orthophoto of the research area situated between Pasar Banggi and Tireman Village of Rembang District, Central Java, Indonesia and digital terrain model of the study area

The final step was generating a tile model of the orthophoto and DSM (Figure 2). Photo alignment was performed to produce an initial 3D model, using the GCPs as references. The dense point cloud, containing millions of spot heights from the initial 3D model, was converted into a mesh, and then textured to create a physical 3D model of the study area. Noise filtering and surface smoothing were applied to the DSM using inverse distance weighting. The final spatial resolution of the DSM and orthophoto is 16 cm. This high resolution made it easy to delineate the mangrove area, as indicated by the red dashed line in Figure 1.A.

Shum and Kuo (2010) noted that the accuracy of 3D models from aerial photos relies on the availability and distribution of GCPs. In this study, eleven GCPs were set

up and distributed across the study area (Figure 1.A) using a GNSS Efix F7+ receiver with a static method. Next, five Independent Control Points (ICPs) were used for the analysis of the Circular Error Probable at 90% (CE90) and the linear error probable at 90% (LE90). CE90 was employed as a statistical metric to guarantee accurate horizontal positioning (USGS 1999). This method determines that 90% of positional discrepancies lie inside a defined range, utilizing the formula CE90: $1.5175 \times \text{Root Mean Square Error (RMSE)}$, where RMSE indicates the root mean square error (Rogers et al. 2020; Zeybek et al. 2023). Our investigation revealed a horizontal positional error of roughly 3-6 m, determined using the GCPs via the GPS/GLONASS navigation system.

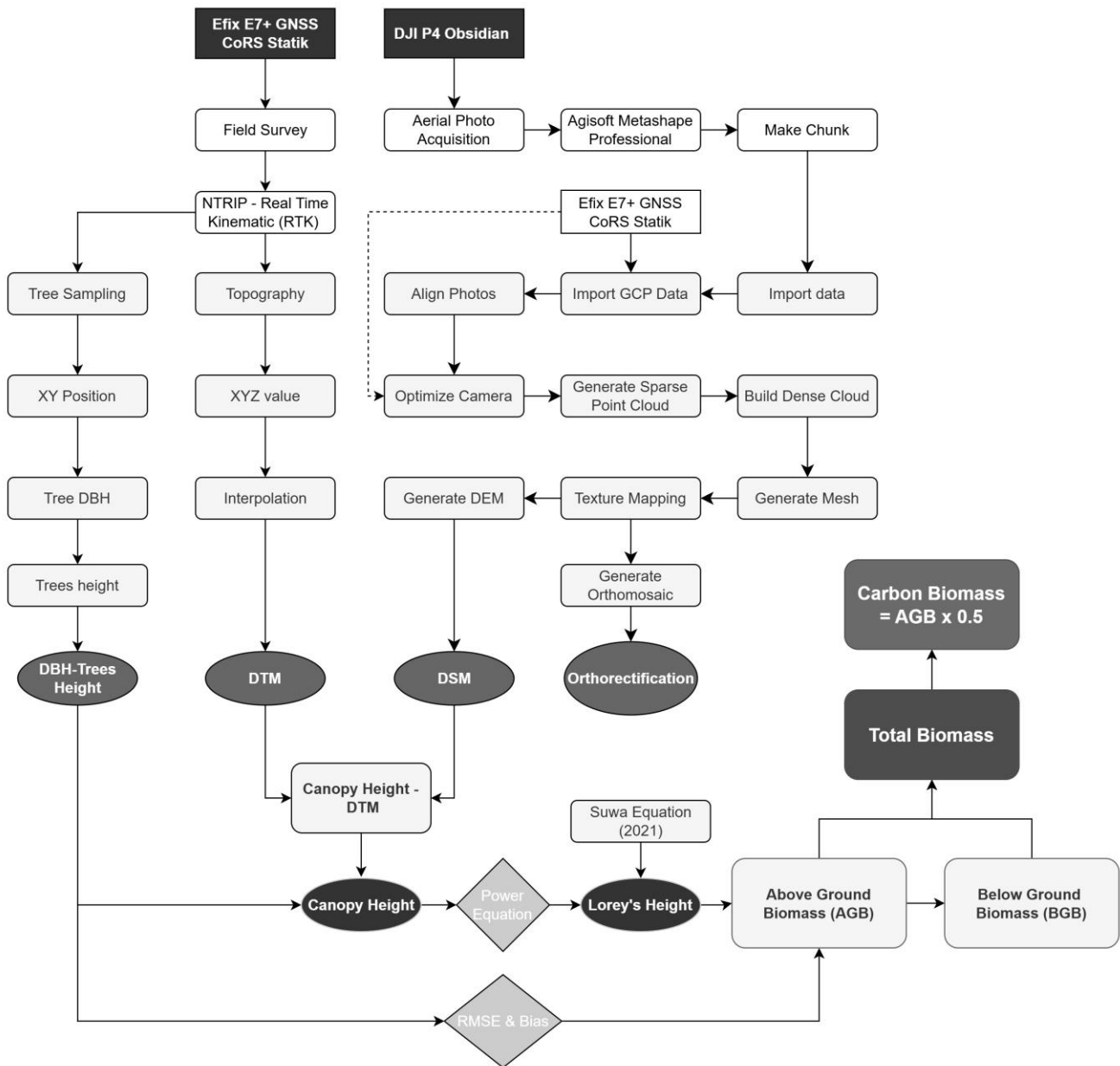


Figure 2. Structure from Motion (SfM) methodology for orthophotos, DSM, canopy height, and AGB

To ascertain the vertical accuracy, we employed the linear error probable at 90% (LE90), guaranteeing that 90% of vertical errors fell within a certain limit. The LE90 number was calculated using the formula $LE90: 1.6499 \times RMSE_z$, where $RMSE_z$ represents the vertical root mean square error. Another GNSS Efix F7+ receiver was used for a topographic survey with the real-time kinematic (RTK) method at 1,945 spots (Figure 1.B), supported by a Continuously Operating Reference Station (CORS) situated 7 km from the study site. The location documented a geoid undulation of 29.016 m utilizing data from the official Indonesian CORS network. The orthometric height values were determined using the formula: $H = N - h$ (Orthometric Height = Geoid - Ellipsoid Height), with height values varying from -0.3140 to 1.6530 m. The vertical error margin for the GCP input throughout processing ranged from 7 to 14 cm, ensuring good precision in the generation of both the DSM and orthophotos, and providing accurate data for subsequent spatial studies. The RTK spots were interpolated to generate the DTM, which represents the ground surface elevation relative to mean sea level (Figure 1.B).

Structure from Motion (SfM) is a photogrammetric technique that is employed to reconstruct three-dimensional (3D) structures from overlapping two-dimensional (2D) images that have been acquired from multiple viewpoints. Figure 2 demonstrates the application of that technique. This method was implemented to derive orthophotos, Digital Surface Models (DSM), canopy height models, and estimate Above-Ground Biomass (AGB). The procedure began with data acquisition via the GNSS Efix F7+ to provide exact XY and XYZ coordinates, facilitating the generation of a Digital Terrain Model (DTM) and the collection of tree attributes, including the Diameter at Breast Height (DBH) and tree height. The DJI P4 Pro Obsidian concurrently acquired aerial imagery, which was subsequently processed with Agisoft Metashape. This encompassed procedures such as importing GCPs, aligning images, optimizing the camera, and producing dense point clouds and meshes to produce the DSM and orthophotos. The canopy height was calculated by subtracting the DTM from the DSM. The canopy heights were transformed into Lorey's height by power equations and were further utilized to estimate the AGB using the equation of Suwa et al. (2021), assuring precise biomass estimations for the mangrove carbon assessment.

Mangrove survey

The mangrove survey was conducted from 3 to 4 March 2024 at 80 sampling points distributed throughout the study area that represent various canopy height conditions (Figure 1.A). This research documented the X and Y coordinates with centimeter-level accuracy utilizing GNSS and recording the DBH, tree height, and species classification. At each sampling point, this research selected an individual tree to assure the position precision for the calculation of biomass allometry, adhering to the methodology described by Suwa et al. (2021).

This study employed both field measurements and aerial mapping for model validation (Wirasatriya et al. 2022; Basyuni et al. 2023, 2025a, b). The tree height was

measured with a pole stick, and the DBH was measured using a standard tape at 1.3 m above ground level. The data gathered on tree height and the DBH were essential for updating the DSM, estimating Lorey's height, and calculating the AGB. Of the 80 sampling points, 27 were used for estimating Lorey's height by investigating the relationship between the estimated canopy's height and Lorey's height using a regression equation, while another 27 points were utilized to validate the estimated Lorey's height (Figure 1.A).

Lorey's height (H_m ; Suwa et al. 2021) is computed as the weighted mean height of trees at each location, utilizing each tree's Basal Area (BA) as a weighting factor, where H represents the tree height and BA denotes the basal area, which is derived by:

$$H_m = \frac{\sum_{i=1}^N (BA_i \times H_i)}{\sum_{i=1}^N BA_i}$$

$$BA = \pi \times \left(\frac{DBH}{2}\right)^2$$

This terrestrial survey data was essential for validating drone-based models, guaranteeing accurate biomass calculation, and identifying changes in land cover over time. The GNSS accuracy in the survey ensured high-precision georeferencing, augmenting the dependability of the produced DSM and canopy height models, which underpin subsequent spatial-temporal analysis.

Calculation of mangrove biomass

The research utilized the height-biomass relationship model established by Suwa et al. (2021) to measure the AGB of mangroves, especially developed for mangrove ecosystems in Southeast and East Asia (Figure 3). The IPCC (2019) approach is employed for the estimation of BGB. IPCC (2019) utilizes specialized formulae based on localized data related to specific regions or species, resulting in findings that are more accurate than traditional ratios. To estimate BGB, IPCC (2019) formula employs the AGB data and a root-to-shoot ratio (R) of 0.39 in the tropical forest (Figure 3). Total biomass consists of the sum of AGB and BGB measurements.

Where H_m represents Lorey's height, defined as the basal area-weighted height of all trees within the stand. This index is regarded as very precise since it prioritizes larger trees, hence more accurately representing the height of the tallest trees in the stand (Lefsky 2010; Shapiro 2024). Since stand biomass (mg/ha) is mostly affected by the height of canopy trees, which are often taller, Lorey's height is an effective indicator for estimating stand biomass. Numerous studies have confirmed its relevance for biomass estimation (Saatchi et al. 2011; Simard et al. 2019; Suwa et al. 2021). Suwa et al. (2021) especially noted that Lorey's height demonstrates a more robust link with biomass data than the arithmetic mean height (unpublished data). Consequently, Lorey's height has emerged as a favored metric for estimating canopy height in biomass research.

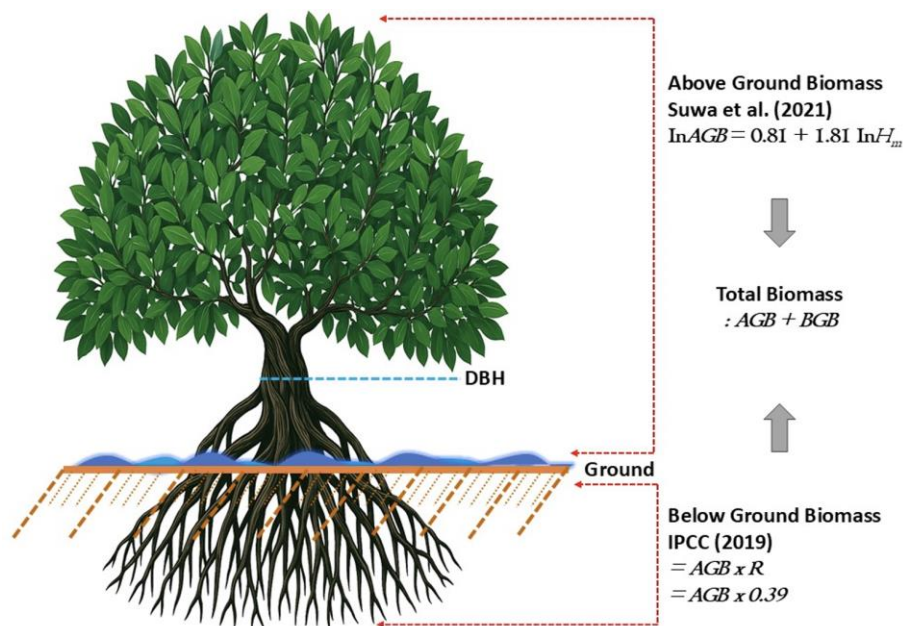


Figure 3. Above-Ground Biomass (AGB) is computed using the equation from Suwa et al. (2021), whilst Below-Ground Biomass (BGB) is determined using the default root-to-shoot ratio from the IPCC (2019), with total biomass calculated as the sum of AGB and BGB

Prior studies have shown that disparities in the height-biomass relationship among species are predominantly influenced by variations in the DBH, wood density, and tree height (Chave et al. 2005; Komiyama et al. 2005). When this methodology was applied to mangrove stands, Suwa et al. (2021) identified significant differences in Lorey's height-biomass relationships between closed-canopy and open-canopy mangroves. Nonetheless, under closed-canopy forests, including the mangroves of the Karimunjawa-Kemujan Islands, no notable differences in height-biomass associations were detected among several mangrove species. Thus, the height-biomass equation established by Suwa et al. (2021) is appropriate for our research location, which also encompasses a closed-canopy mangrove forest. To ensure the accuracy of this analysis, the remaining 26 sampling points were used for biomass validation (Figure 1.A).

Accuracy assessment

The systematic approach calculates both bias and RMSE to assess the efficacy of predictive models in Figure 2 (Hu et al. 2020; Amuyou et al. 2022; Hodson 2022). Initially, a dataset is assembled that includes the observed values (DBH and tree height) obtained from the field survey, together with the corresponding predicted values (AGB models) produced by the UAV model (Wirasatriya et al. 2022; Basyuni et al. 2023). To determine the bias, we calculate the mean of the discrepancies between the observed and anticipated values.

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

Where, (n) signifies the number of observations, (y_i) indicates the observed values, and (\hat{y}_i) denotes the anticipated values. The bias value offers insights into the predictive inclinations of the model. When bias approaches zero (bias \approx 0), it signifies that the predictions closely correspond with the observations. A positive bias (bias > 0) indicates a propensity to underestimate the observed values, whereas a negative bias (bias < 0) signifies a tendency to overestimate them. This statistic is crucial for assessing the systematic inaccuracy in prediction models. To calculate the RMSE, we first determine the squared differences between the observed values (DBH and tree height) from the field survey and the predicted values (AGB models) produced by the UAV model (Wirasatriya et al. 2022; Basyuni et al. 2023). Next, we compute the mean of these squared differences, and finally, we take the square root of the result.

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

The computation of the RMSE entails a sequence of procedures to assess the precision of a predictive model. Initially, the squared discrepancies between the observed values (y_i) and the anticipated values (\hat{y}_i) were computed. Subsequently, we calculated the mean of these squared deviations to encapsulate the whole error magnitude. Finally, we computed the square root of this mean to derive the RMSE value. This metric offers a thorough evaluation of model accuracy by encompassing both systematic mistakes (bias) and random errors, hence providing a complete assessment of predicted performance.

RESULTS AND DISCUSSION

Canopy and Lorey’s heights

The DSM analysis reveals the height distribution of mangrove canopies within the study area, with elevations ranging from 0 m to 15 m (Figure 4.A). The topography of Pasar Banggi and Tireman is classified as a flat sedimentary plain, with surface elevations between 0 m and 1.8 m (Figure 1.B). The calculated mangrove canopy height varies significantly across sites, ranging from 0 m to 15.3 m (Figure 4.B). The tallest canopies are observed along the southern edge, closer to the mainland and near the shrimp farms, where the area is more sheltered from the sea. Meanwhile, higher canopy heights are concentrated in closed regions of Pasar Banggi, especially near the central

areas close to the base. When comparing Figures 3.B and 1.A, a clear correlation is observed between canopy height and mangrove density (Figure 5.A), with denser areas supporting taller trees. Conversely, lower canopy heights are associated with sparser mangrove distributions. Given that the topographies of the Pasar Banggi and Tireman regions are relatively uniform, with minimal variation in elevation (0-1.8 m), it can be concluded that the height variation in mangrove canopies is more influenced by sheltering and density than by topographic elevation (Figure 1.B). These findings provide critical insights into the spatial distribution of mangrove heights and their relationship to local environmental factors.

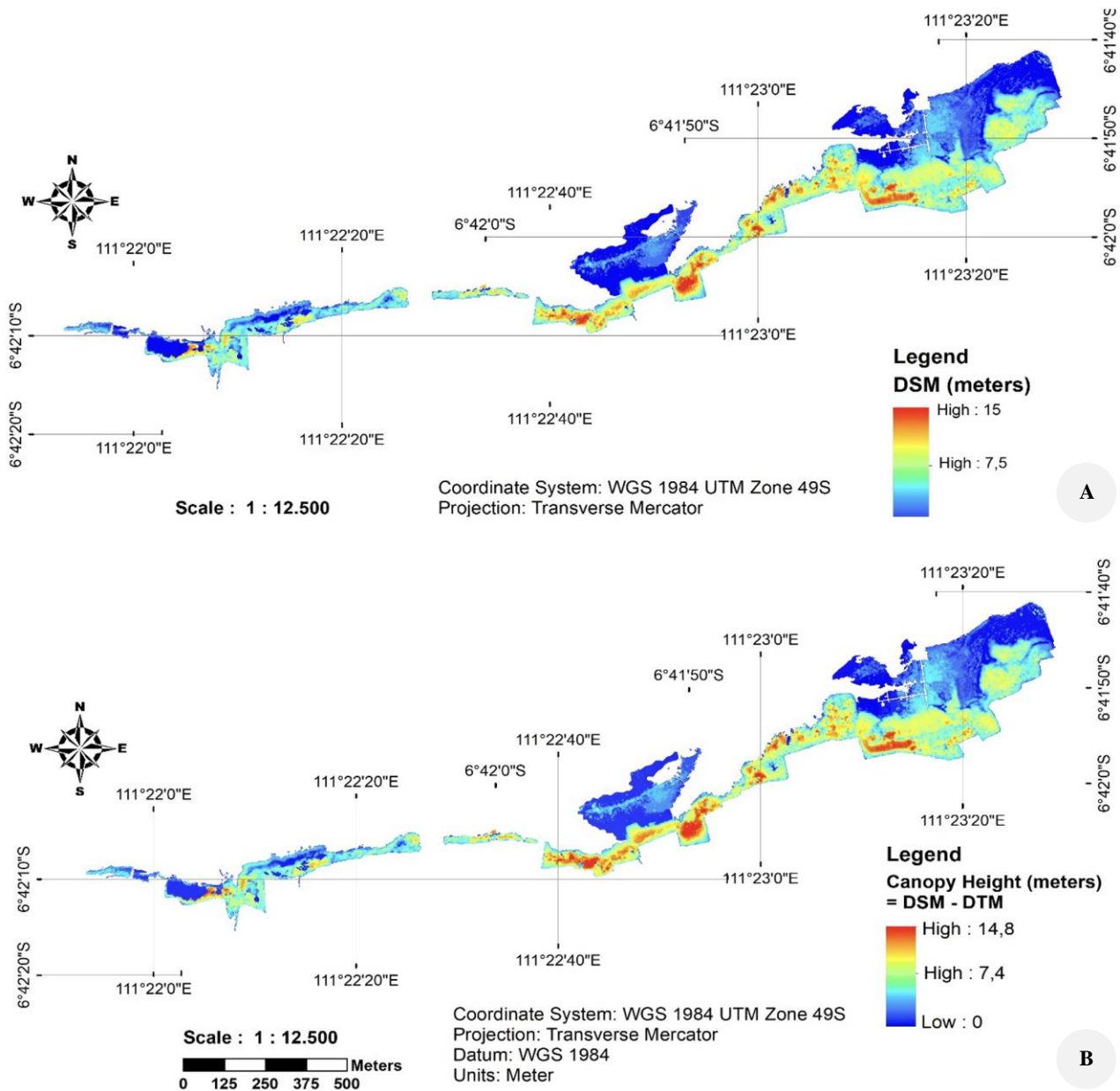


Figure 4. A. The SfM methodology for the orthophotos DSM; B. The SfM methodology for the orthophotos canopy height

The relationship between the calculated canopy height and the observed Lorey's height is illustrated in Figure 5.A. The results show that the calculated canopy heights are generally higher than the observed Lorey's heights, following an exponential trend with a strong correlation ($R^2: 0.96$). This indicates a high degree of accuracy in the model. The conversion from calculated canopy height to Lorey's height based on aerial photography can be expressed using the equation:

$$y = 0.9296x^{1.043}$$

Where, y represents the calculated Lorey's height and x denotes the calculated canopy height. This formula provides a reliable method for estimating Lorey's height from canopy height, facilitating more precise vegetation assessments from aerial data. The high determination coefficient underscores the robustness of the relationship, making this conversion method suitable for large-scale mangrove forest studies.

This investigation confirmed the computed Lorey's height against the observed Lorey's height from Suwa et al. (2021) (Figure 4.B), and the RMSE shown in the data can be utilized to calculate AGB. The scatter plot analysis reveals a close correlation, a bias value of -0.215 m, and a RMSE of 0.451 m. Although this level of error is slightly higher than in previous studies (<0.1 m; Otero et al. 2018; Kustiyanto 2019; Jones et al. 2020), it remains within an acceptable range. The elevated error in our study may be attributed to the lower accuracy of the GNSS devices used under the dense mangrove canopy, which likely resulted in positional discrepancies between the estimated and observed Lorey's heights. The RMSE in this study is significantly lower than the 3.7 m reported by Aslan et al. (2016) for mangrove canopy heights in Papua utilizing SRTM data with a 30 m resolution. Given that the maximum Lorey's height in our study is approximately 15 m, an RMSE of 0.45 m is considered acceptable for vegetation height assessments. These results underscore the viability of our method for future large-scale mangrove height estimations.

By applying Equation (4) to the canopy height distribution (Figure 4.B), we derived the spatial distribution of Lorey's height, as depicted in Figure 5. The Lorey's height in the study area ranges from 1 m to 15.3 m, with the highest values observed in the south, near the base and salt ponds. In this southern region, Lorey's height frequently exceeds 15 m. In contrast, the northern area, closer to the sea, is dominated by smaller mangrove saplings, particularly from restoration efforts. In the northwest, which is bordered by the sea and characterized by white sand sedimentation, Lorey's height reaches over 5 m, indicating less favorable conditions for mangrove growth compared to the southern side. Overall, the data reveals a distinct boundary, forming a narrow band of higher Lorey's heights along the seaside. These heights are comparable to those found in other mangrove areas in Indonesia, such as Karimunjawa in Central Java (Wirasatriya et al. 2022), Lubuk Kertang in North Sumatra (Basyuni et al. 2023), and the Mahakam Delta in Kalimantan (Kustiyanto 2019). However, they are

considerably shorter than mangroves in Papua, where heights can exceed 40 m. This variation underscores the diverse environmental conditions affecting mangrove growth across Indonesia.

The restored mangroves in the northern section are characterized by shorter mangroves, averaging around 1 m in height, with only 4 to 10 leaves per plant. Figure 6 shows the low-density, blue-colored areas representing these restored mangrove saplings. The lowest Lorey's height is observed at the northeastern tip of the region. On the northwestern side, a large river borders the mangroves, which are shorter than on the other side, possibly due to significant sand sedimentation forming a sandbar. This area is adjacent to a tourism site located across the river to the west.

Above and below-ground biomass

The assessment of the AGB is intricately associated with Lorey's height, indicating the biomass distribution throughout the mangrove forest. Consistent with Suwa et al. (2021) this research indicates that increased Lorey's heights are associated with higher AGB values, a pattern observable in mangrove areas next to fish and salt ponds, which spatially exhibit heightened biomass levels. The seaward expansion of the mangroves is marked by the presence of young trees, roughly 0.3 m in height, signifying ongoing rehabilitation efforts in the region. These mangroves signify the preliminary recovery phases of the ecosystem, resulting from conservation efforts.

The 36 -hectare Mangrove Pasar Banggi forest exhibits an AGB ranging from 6 to 317 mg/ha, with a mean value of 53.4 mg/ha (Figure 7.A). To evaluate the reliability of the AGB estimation, we juxtaposed conventional field measurements with data acquired via UAV photogrammetry. The analysis indicated an RMSE of 8.95 mg/ha and a bias of 0.12 mg/ha, signifying a high degree of accuracy (Figure 5.C). The biomass distribution is significantly concentrated in the southern region, impacted by nearby rivers, which facilitate a more abundant and denser mangrove ecosystem with elevated AGB values. This research validates that UAV photogrammetry is a dependable and effective method for biomass assessment in mangrove environments.

The regional distribution of BGB and total biomass exhibits a consistent pattern (Figure 7.B), wherein regions with elevated BGB values, spanning from 2 to 123 mg/ha, typically correspond to high total biomass (Figure 7.C), which can attain levels of up to 440 Mg/Ha. The largest concentrations are located in the middle to eastern region of the research area, predominantly characterized by mangrove species with robust root systems, including *R. mucronata* and *R. apiculata*. The linear correlation between BGB and total biomass indicates the substantial role of the root system in facilitating overall carbon buildup. This pattern demonstrates that mangrove restoration in Pasar Banggi has effectively enhanced above-ground vegetation biomass and established a robust ecological foundation through the development of BGB, thereby serving as a viable strategy for ecosystem-based climate change mitigation efforts.

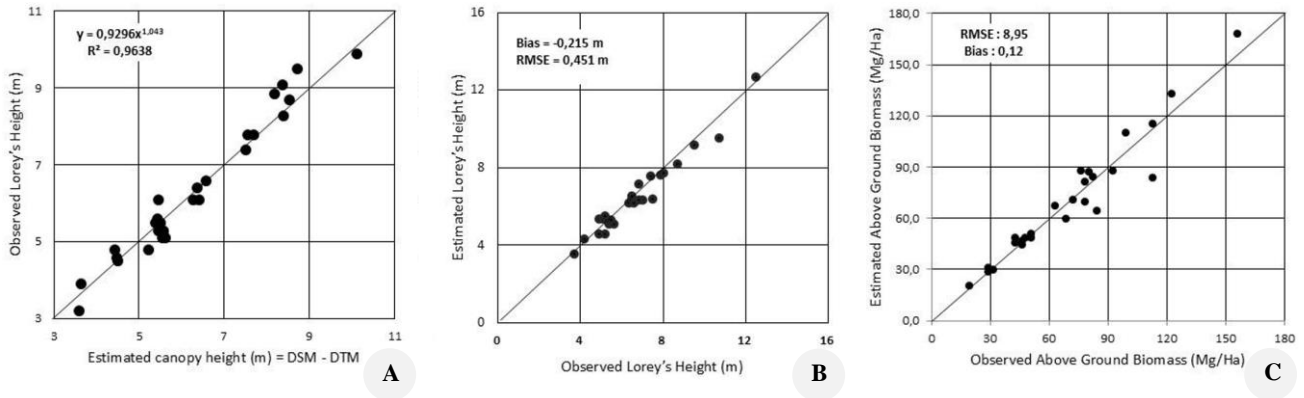


Figure 5. A. Scatter plots of calculated canopy height with observed Lorey’s height; B. Scatter plots of observed and calculated Lorey’s heights; C. Scatter plots of observed and calculated AGB

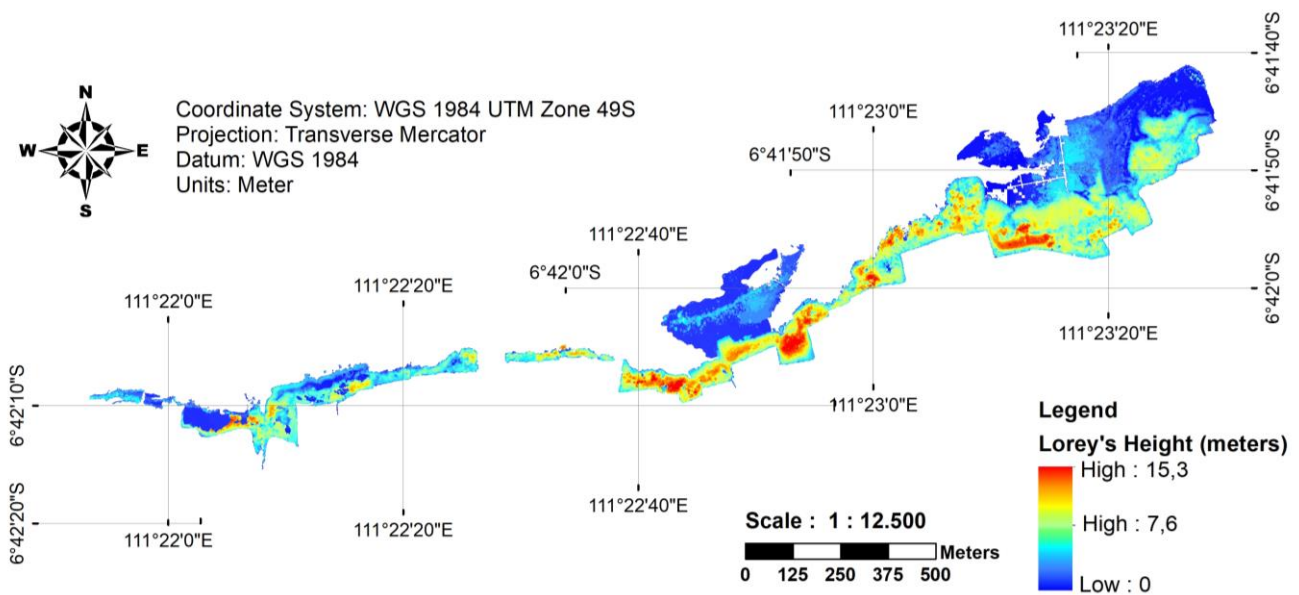


Figure 6. Calculated Lorey’s height of mangroves in the restored areas of Tireman and Pasar Banggi, Rembang, Central Java, Indonesia

Discussion

Pasar Banggi and Tireman possess six species of plants from the dominant group: *R. stylosa*, *R. apiculata*, *R. mucronata*, *A. marina*, *E. agallocha*, and *Sonneratia* (Iryanthony et al. 2025). This study indicates the substantial carbon storage capacity of rehabilitated mangrove ecosystems in Pasar Banggi, Rembang, Central Java, with *R. mucronata*, *R. apiculata*, and *R. stylosa* accounting for 38%, 27%, and 9% of the total biomass, respectively, underscoring their preeminent role in carbon sequestration (Figure 8.B). These findings correspond with Soprobowati et al. (2024), who estimated a total carbon stock potential of 0.02×10^6 mg in the same location, with up to 65% sequestered in sediments, highlighting the significant role of sediment carbon pools in carbon stock evaluations. The application of UAV-based monitoring and species-specific allometric models accurately quantified AGB and BGB, underscoring their significance in the

development of MRV systems for blue carbon efforts. Although reduced biomass was seen in species like *A. marina* and *E. agallocha*, their existence enhances ecological resilience, highlighting the necessity of balancing biomass maximization with biodiversity in restoration approaches.

Furthermore, Soeprobowati et al. (2024) identified five species, whereas Rahmat et al. (2022) identified six species, with *R. stylosa*, *R. apiculata*, and *R. mucronata* being predominant. The contrast of our research with the methodology employed by Soeprobowati et al. (2024) for AGB estimation reveals several approaches, each with its own merits. Soeprobowati et al. (2024) employed a field-based allometric approach -DBH- to estimate AGB, utilizing species-specific allometric equations. This procedure is conventional and broadly recognized, however, it is laborious and restricted in spatial extent.

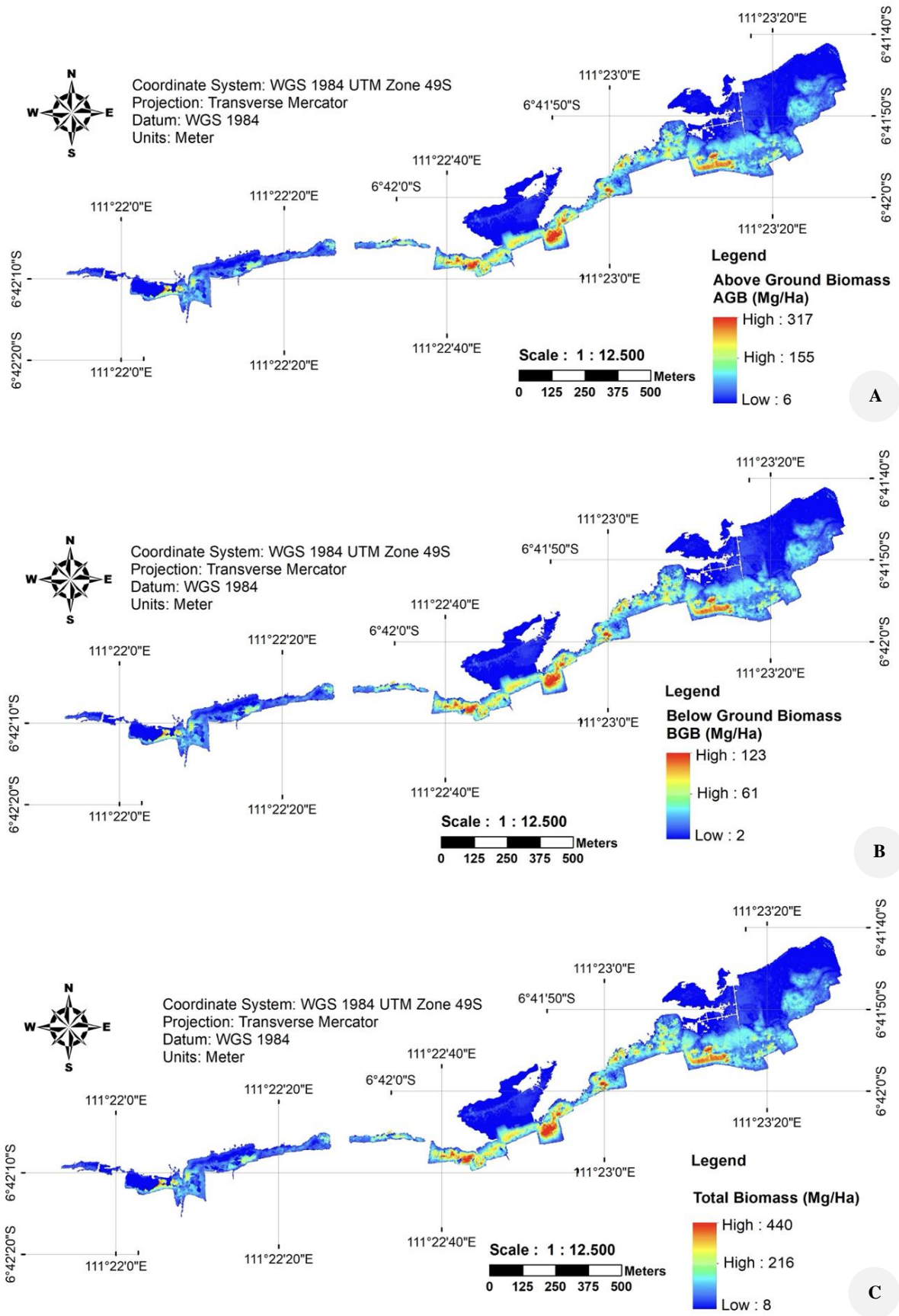


Figure 7. A. Above ground; B. Below ground; C. Total biomass of mangroves in Tireman and Pasar Banggi, Rembang, Central Java, Indonesia. In Pasar Banggi, the lowest biomass is in the northern region (mangrove saplings), followed by the adult mangrove in the southern region

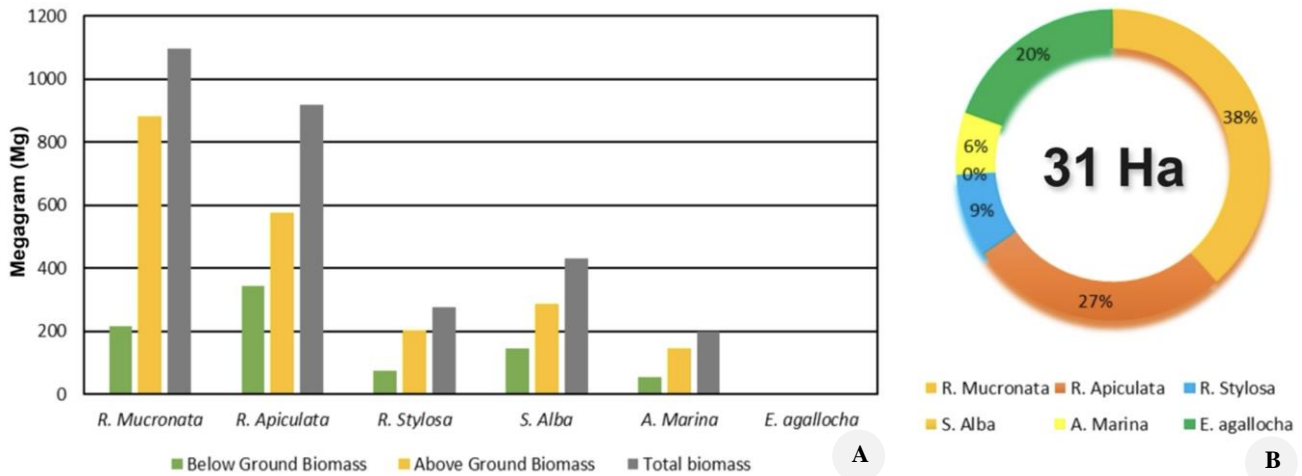


Figure 8. A. Above-ground, below-ground, and total biomass (kg) of dominant mangrove species in the restored area of Pasar Banggi, Rembang, Central Java, Indonesia; B. Proportional contribution (%) of each mangrove species to total biomass

Conversely, our research employed UAV-based photogrammetry combined with DBH-tree height (utilizing GNSS positional precision), facilitating extensive coverage, and employing Lorey’s height as a surrogate for AGB estimation. Our UAV methodology enhanced efficiency by recording biomass distribution over an extensive area; however, it encountered minor accuracy issues beneath dense canopies. Soeprbowati et al. (2024) reported an AGB range of 92.49 to 286.74 mg/ha, but our analysis identified a broader range of 6 to 317 mg/ha. This may be due to the mangrove stands being in varying states of restoration, including newly recovered areas with mangrove saplings less than 1 m in height. Both investigations utilized allometric equations, with Soeprbowati et al. (2024) concentrating on species-specific computations and our research employing a model designed for Southeast Asian mangroves. The precision of the AGB estimates fluctuated. Their method had the highest correlation with field data, but our UAV method achieved an RMSE of 8.95 mg/ha, demonstrating that UAV photogrammetry is an effective instrument for assessing extensive mangrove biomass.

The mean AGB mangrove in Pasar Banggi is 53.4 mg/ha, with a range of 6 to 317 mg/ha, consistent with other research findings. Wirasatriya et al. (2022) recorded the AGB in Karimunjawa between 8 and 328 mg/ha, with a mean of 69.27 mg/ha, and noted a Lorey’s height bias of -0.04 m and an RMSE of 1.28 m. The present analysis exhibits a bias of -0.215 m and an RMSE of 0.451 m for Lorey’s height, indicating analogous patterns in biomass variability. Suwa et al. (2021) emphasized the likelihood of the systematic underestimating of AGB in mature mangroves over 400 mg/ha; nevertheless, Equation (3) is still relevant for AGB beneath this threshold, as evidenced by our research. Basyuni et al. (2023) showed AGB ranging from 0 to 173.8 mg/ha in restored mangroves and 16 to 140 mg/ha in natural mangroves, which aligns with our findings. Discrepancies in AGB calculations may arise from differences in mangrove species and growth stages, as

species such as *R. apiculata*, which has an AGB of roughly 270 mg/ha, need about five years to attain a height of 3 m (Qiu et al. 2019; Beselly et al. 2021). Furthermore, the AGB throughout the mangrove land cover types in Budeng-Perancak, Bali varied from 2 mg/ha to 480 mg/ha, with a mean of 240 mg/ha (Basyuni et al. 2025b). The highest average total AGB was seen in wild mangroves (239 mg/ha), followed by restored mangroves (232 mg/ha) (Basyuni et al. 2025b). Mangrove forest in Lubuk Kertang Village has lost around AGB 56% due to illegal from 2023 to 2024 (Basyuni et al. 2025a). These findings highlight the uniformity of AGB estimation approaches across various mangrove ecosystems.

The prior research conducted by Tianyu (2020), employing multisource remote sensing, attained an RMSE of 75.85 mg/ha and an R² of 0.48, indicating moderate accuracy. In contrast, the UAV-based methodology utilized in this study yielded a markedly lower RMSE of 2.92 mg/ha and an R² of 0.9946, signifying superior precision in AGB estimation through UAV imagery. In 2017, Fatoyinbo et al. (2018) demonstrated a strong correlation between aerial LiDAR data and AGB estimates in the Zambezi Delta, with an R² value ranging from 0.80 to 0.88 and an RMSE as low as 33%. Rocha et al. (2018) reported RMSEs of 11.2 mg/ha for calibration and 14.8 mg/ha for validation, utilizing species-specific models. In contrast to prior studies, the UAV-based methodology in our research provides a more localized, high-resolution option, especially appropriate for small-scale mangrove habitats such as Pasar Banggi. Consequently, the method remains viable in comparison to alternatives such as LiDAR, which offers greater accuracy and more extensive data, and techniques such as GCP analysis, with vertical-horizontal precision, DSM generation and evaluation. In conclusion, the present study emphasizes how important it is to preserve and restore mangroves. The utilization of UAV data offers the most economical alternatives for estimating AGB with comprehensive spatial distribution.

A thorough investigation of the constraints of UAV techniques beneath dense canopies reveals their inability to produce DTM. An effective approach is utilizing GNSS data to produce a DTM and acquire accurate position samples, as indicated in the prior studies (Wirasatriya et al. 2022; Basyuni et al. 2023). The LiDAR approach (Gao 2023; Tian 2023), which produces a Canopy Height Model (CHM) independently of DTM, can effectively detect terrain elevation. To achieve optimal cost-effectiveness, we chose the photogrammetry method, given that the LiDAR method is significantly more expensive (tenfold). AGB requires ground adjustment based on the DBH in field studies, even when utilizing LiDAR data (Qiu et al. 2019). During the collection of the DBH data, we utilized the Real-Time Kinematic (RTK) method for topographic data acquisition, which is more efficient in terms of time and budget.

This work demonstrates the effectiveness of UAV-based photogrammetry and GNSS technology in evaluating AGB in mangrove ecosystems, specifically in the blue carbon-rich mangrove habitats of Pasar Banggi and Tireman, Rembang District, Central Java, Indonesia. Utilizing high-precision digital surface and terrain models, we acquired canopy height estimations with horizontal and vertical accuracies (CE90 and LE90) of 0.0201 m and 0.0249 m, respectively. The findings reveal AGB levels ranging from 6 to 317 mg/ha, illustrating the variability in mangrove stand maturity, from saplings to fully grown trees. Our UAV methodology attained an RMSE of 2.92 mg/ha, strongly correlating with field-based observations and exhibiting considerable precision in biomass estimation across extensive regions. The method of AGB estimation using UAV imagery also has been successfully applied in Karimunjawa (Wirasatriya et al. 2022), North Sumatra (Basyuni et al. 2023, 2025a) and Perancak, Bali (Basyuni et al. 2025b) with high accuracy. Thus, this method offers a cost-effective, scalable alternative to LiDAR for the extensive, high-resolution monitoring of carbon stocks in coastal ecosystems, despite minor constraints beneath dense canopies. The alignment of our findings with prior research highlights the reliability of allometric models tailored for Southeast Asian mangroves and reinforces the efficacy of mangrove restoration as a feasible approach to carbon sequestration. Our research confirms the importance of protecting mangroves as essential blue carbon resources, advocating for UAV-based methods as effective tools for consistent monitoring and sustainable coastal management techniques. Noting that, the application of this method in Rembang, Karimunjawa, North Sumatra and Bali is limited to the low diversity of mangrove as denoted by less than 10 species domination. Thus, further examination should be performed in natural mangrove forest with high diversity to ensure the accuracy of estimated AGB using UAV for various condition of mangrove.

The high-resolution biomass estimates derived from UAV and GNSS integration in this study provide a critical foundation for establishing standardized Monitoring, Reporting, and Verification (MRV) frameworks essential for blue carbon credit mechanisms. These data align with the methodological requirements of IPCC Tier 2/3

reporting, supporting Indonesia's commitment under its Nationally Determined Contributions (NDCs). Furthermore, the spatially explicit carbon stock maps can inform national conservation planning, particularly within the framework of the National Mangrove Map and the Essential Ecosystem Area program. This reinforces the case for scaling up mangrove restoration in Pasar Banggi and similar regions, leveraging carbon finance to promote sustainable coastal development and biodiversity conservation.

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