# Estimation of mangrove above-ground carbon stock using unmanned aerial vehicle in the community forest area in Deli Serdang, North Sumatra, Indonesia

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**Abstract**. Mangrove forests are vital ecosystems that provide many ecological, economic, and social benefits. Mangrove forests are effective to mitigate and adapt to the climate crisis. Mangroves act as carbon absorbers, absorbing inorganic carbon ($CO_2$) and converting it into organic carbon in the form of plants. Mangrove ecosystems are crucial for carbon storage, as they rank among the ecosystems with the highest carbon density on the planet. One climate change mitigation effort that can be implemented is optimizing the role of mangroves in photosynthesis. Unmanned aerial vehicles (UAVs) can help efficiently analyze the carbon content in mangrove forests. The mangrove forest in Tanjung Rejo village still covers a fairly large area with moderate to high vegetation density, making it very important to conduct further research to assess its carbon storage potential as one of its ecosystem services.This research aims to assess the carbon storage located above the ground by estimating the above-ground biomass (AGB) in mangrove ecosystems using UAV technology. The study combines aerial imagery captured by UAVs with geodetic GPS data to produce precise Digital Surface Models (DSM) and Digital Terrain Models (DTM). The mangrove canopy's height was calculated by subtracting the DTM from the DSM, and this value was then transformed into Lorey's height (LH). Furthermore, field measurements were taken to record the diameter at breast height (DBH) of the mangroves as a basis for calculating LH, which was subsequently used to estimate mangrove biomass. In Tanjung Rejo village, the tallest recorded mangrove canopy reached a height of 29 meters, located on the southwestern and northern edges of the forest. AGB and carbon stock estimates for mangroves in Tanjung Rejo village ranged from 9 to 758 Mg ha$^{-1}$ for AGB and 4 to 379 MgC ha$^{-1}$ for carbon stock, with a study area of 21 hectares. The estimated amount of carbon stored above ground within the study area has been calculated to be 7,959 MgC.

**Key Words**: blue carbon, mangrove carbon stock estimation, mangrove forest restoration, unmanned aerial vehichle application.

**Introduction**. Mangrove forests constitute essential coastal ecosystems that deliver a wide range of environmental, economic, and social services. These forests support biodiversity by providing habitats for various species, reduce the impact of coastal erosion through their natural buffering function, and contribute significantly to climate regulation by capturing and storing atmospheric carbon (Wirasatriya et al 2022; Rull 2024). Protecting mangrove forests is an effective method for mitigating and adapting to the climate crisis. Mangroves absorb inorganic carbon ($CO_2$) and convert it into organic carbon in plant form. Most ecosystems break down substances and release carbon into the atmosphere (Sulaiman 2023). The strategy for mitigating climate change is to maximize the role of mangroves in photosynthesis (Nedhisa & Tjahjaningrum 2020). Mangroves absorb $CO_2$ through the process of photosynthesis, plants transform this energy into carbohydrates, storing it as biomass within their root systems, stems, and leaves (Suryono et al 2018).

Research on carbon stock estimation is very much needed to support global climate improvement efforts. This is because the world is currently facing a global crisis known as climate change. Remote sensing applications serve as a research method for obtaining spatial data for environmental mapping and observation over large areas, addressing the limitations of traditional mangrove surveys. Unmanned aerial vehicles (UAVs) serve as a tool for gaining a more in-depth understanding of mangrove ecosystems through enhanced monitoring (Thoha et al 2022).

Mapping carbon stocks provides important understanding of how carbon is distributed across space within altered landscapes, helping to assess the environmental impacts of land-use changes. Conducting large-scale carbon stock assessments provides crucial insights into the spatial distribution of carbon and how it changes over time in relation to emissions (Haris et al 2021). Evaluating carbon stocks in mangrove ecosystems plays a key role in advancing strategies to reduce carbon emissions. The use of open-source data offers an efficient balance between precision, affordability, and time management (Wang et al 2021).

Open-source data can be utilized in remote sensing technology to conduct large-scale digital mapping, enabling the identification of mangrove forests and the estimation of their carbon stock across Indonesia (Rudiyanto et al 2018). UAV aerial photos combined with GPS geodetic measurements will result in more accurate data. When compared to manual mapping, drone-based mapping is faster and easier. Furthermore, mapping with drones does not cost much compared to manual methods or satellite mapping using paid software. The resulting data will be accurate because UAV aerial photos have high resolution and can reach inaccessible areas (Arinah et al 2021).

Located near the coast, the majority of Tanjung Rejo village consists of marine and coastal waters with significant potential for fisheries, tourism, and mangrove forest development. However, many mangrove forests in the area have been converted for other uses, including oil palm plantations, aquaculture, and residential areas. It is widely recognized that mangrove forests face ongoing disturbances from both human activities and environmental factors. Such disturbances, including changes in land use, heighten the vulnerability of mangroves to climate change, including increased sea levels and the deterioration of ecosystems (Akbar et al 2017; Harefa et al 2022). The objective of this research was to assess the above-ground biomass and the carbon storage potential of community mangrove forests using UAV technology.

## Material and Method

***Description of the study sites***. Tanjung Rejo village, located within the Percut Sei Tuan district of Deli Serdang Regency in North Sumatra Province, forms a part of the eastern coastal region of Sumatra. Covering an area of 19 square kilometers, the village has a population of 10,342 residents. The mangrove forest within Tanjung Rejo spans approximately 602.181 hectares (Mahmuda et al 2023). This study was carried out between March and December 2023, and the research location is illustrated in Figure 1.

***Materials and data***. The tools used in this research include field survey equipment, software, and hardware, including 1-unit DJI Mavic 2 Pro drone, 1 unit smartphone (equipped with DJI GO 4 and Pix4D Capture apps), data cable, 1 unit laptop (with Windows 2010 64-bit, MS 2010, Agisoft Metashape software, ArcMap 10.8, and PCI Geomatica), smartphone camera, geodetic GPS Emlid Reach RS2, Hagameter, Phiband, and writing tools.

The materials used in this study include administrative maps of the study area, aerial photos captured with the drone, and materials from previous studies and various reference books to support field research.

***Data collection***. Primary data was obtained from aerial photo acquisition using UAVs or drones, which was conducted directly in Tanjung Rejo village. The aerial imagery was captured through the use of UAV technology. To obtain the photos, a mapping mission was set up using the DJI Mavic 2 Pro drone in combination with the Pix4D software application. In this study, 4 Ground Control Points (GCPs) were established and distributed proportionally across the study area.

This study employed a purposive sampling technique to collect data on tree species, tree heights and tree diameters. This method involves selecting participants deliberately based on specific criteria for determining and selecting samples based on specific considerations by the researchers (Sugiyono 2015; Maharani & Bernard 2018). In this study, the area to be identified was 21 hectares.

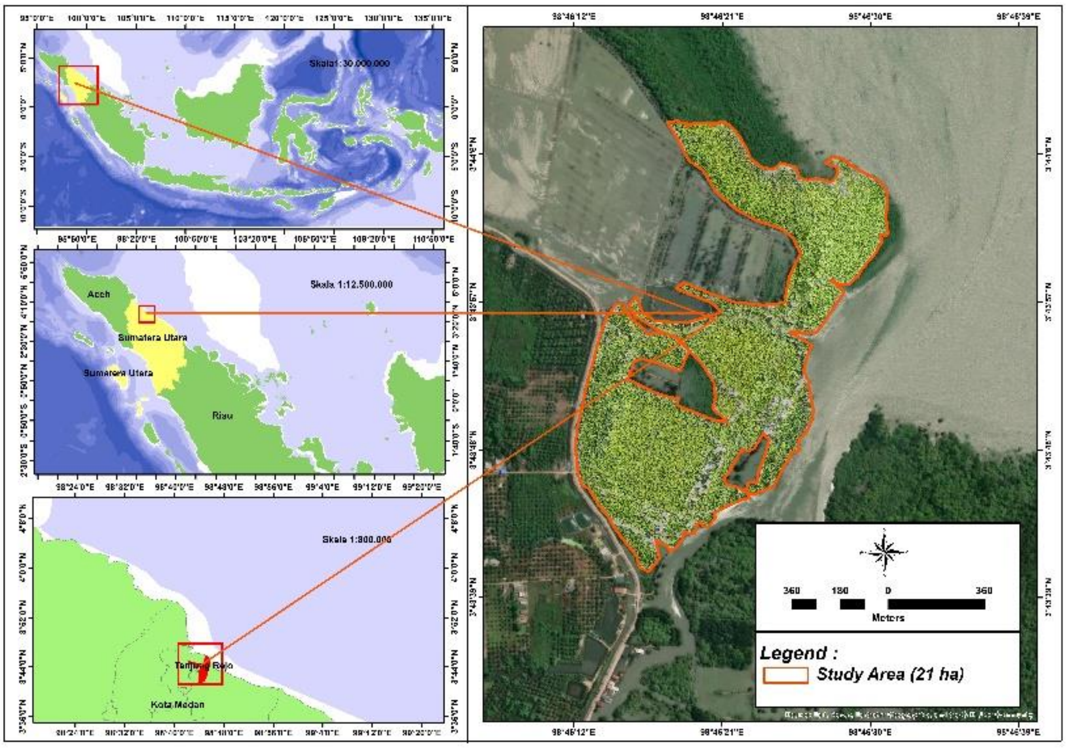


Figure 1. The study area map: orthophoto map (right) and geographic location in Indonesia Country scale (above left), Sumatra Island scale (centre left) and regency scale (below left).

***Aerial photo data processing***. The images captured from the air during the UAV flight operation were processed through several stages including aligning photos, inputting GCPs, building dense clouds, building mesh, building texture, building DEM, and the final step, building orthomosaic. The orthomosaic image was saved in GeoTIFF format, after which the DEM undergone additional processing to generate the Digital Terrain Model (DTM) and the Digital Surface Model (DSM) using PCI Geomatica software.

***Mangrove field survey***. To conduct the mangrove survey, measurements of the arithmetic height and diameter at breast height (DBH) were recorded during the survey. Selecting suitable locations for the mangrove study is crucial due to the lower accuracy of the Global Positioning System (GPS) compared to the Global Navigation Satellite System (GNSS), which is used for referencing UAV photogrammetry. The mangrove trees selected for the survey were chosen for their similar heights at each site to reduce potential discrepancies between data gathered from handheld GPS and GNSS systems. Subsequently, the measured tree heights were adjusted to Lorey's height (LH), which is used to estimate the mangrove biomass. LH was calculated as a weighted average, where each tree's contribution was determined by its basal area. The formulae for calculating LH are outlined in equation 1 (Suwa et al 2020) and equation 2 (Wirasatriya et al 2022), as follows:

$$H_m = \frac{\sum_i^N BA_i \: x \: H_i}{\sum_i^N BA_i} \quad (1)$$

$$BA = \pi \: x \left(\frac{DBH}{2}\right)^2 \quad (2)$$

where Hm, H, and BA denote Lorey's height, arithmetic height, basal area, respectively. The LH, obtained from the red data points, is subsequently used to create a formula that calculates canopy height based on aerial images.

The canopy height model (CHM) measures the vertical gap between the highest points of vegetation and the ground level below. This model provides valuable insights for assessing forest features, including estimating timber volume and tracking forest development (Illarionova et al 2022). To derive the CHM for the study area, the DSM was reduced by the DTM. The CHM was then determined using the formula below:

Canopy height model = DSM – DTM (3)

***Calculation of above-ground mangrove biomass***. Data calculation was performed by analyzing the dataset, with the analysis used to assess the relationship between height, diameter, and above-ground biomass (AGB). Taller trees generally have larger trunk diameters and greater mass. As tree height increases, the volume and mass of the trunk, branches, and leaves also increase. Therefore, a higher LH indicates that the area contains more large trees, which store more biomass (Felpausch et al 2012). The AGB of mangrove forests is calculated using the Hm-AGB equation developed by Suwa et al (2020). This equation, tailored for areas in Southeast and East Asia, is represented by the following formula:

lnAGB = 0.81 + 1.81 lnHm (4)

Stand biomass (measured in Mg $ha^{-1}$) is mainly influenced by trees with expansive, tall canopies, thus LH can serve as a useful parameter for predicting the biomass in a forest stand. Roughly half of the AGB is composed of carbon, according to Aalde et al (2006).

## Results

***Measurement of ground control points (GCP)***. The GCP points obtained after field measurements serve as reference coordinates for processing aerial photo data with a flight height of 60 meters. These points are presented in Table 1, and the distribution of the GCP points is shown in Figure 2.

The X coordinate in the UTM coordinate system shows the position of the GCP point in the horizontal direction (east-west). The Y coordinate shows the position of the GCP point in the vertical direction (north-south). The letter Z is the height of the GCP point above sea level in meters. This data is crucial in map processing and spatial data, especially for georeferencing, which is aligning digital maps or satellite imagery with actual coordinates in the field. The accuracy of the GCPs highly depends on the type of GPS used and the number of GCP samples taken at the location and time of measurement (Sastra et al 2023).

Table 1

Ground control points (GCP)

| *GCP* | *X* | *Y* | *Z (m)* |
|---|---|---|---|
| 1 | 474610.842 | 412017.835 | 2.578 |
| 2 | 474550.531 | 412561.065 | 1.959 |
| 3 | 474860.132 | 412686.795 | 2.290 |
| 4 | 474658.358 | 412395.809 | 2.485 |

Note: Using the Universal Transverse Mercator (UTM) Projection, Zone 47N.

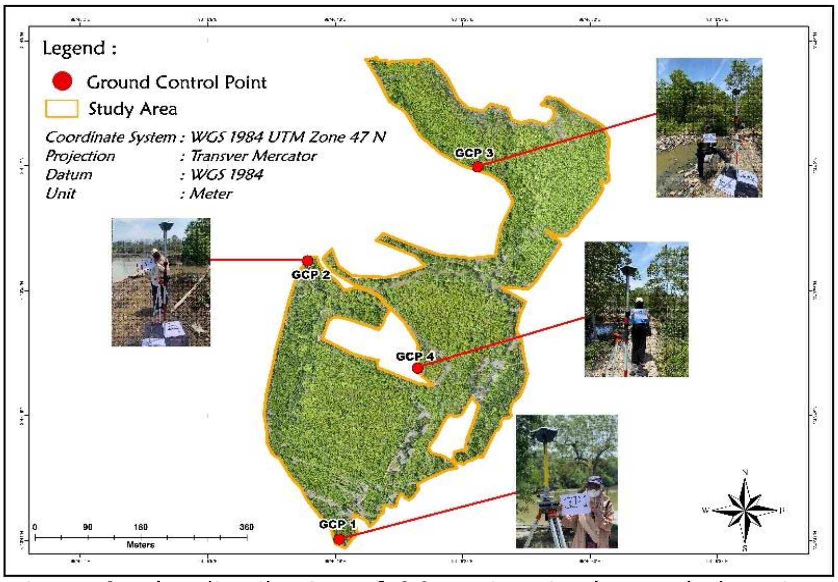


Figure 2. The distribution of GCP points in the study location.

***Estimation of tree canopy height and Lorey's height***. The height measurements obtained from the DSM indicate that the vegetation canopy and mangrove areas at the study site vary between 0 m and 30 m (see Figure 3a). In contrast, the height estimation using equation 3 shows that the range for the vegetation canopy and mangrove areas extends from 0 m to 29 m, as illustrated in Figure 3b.

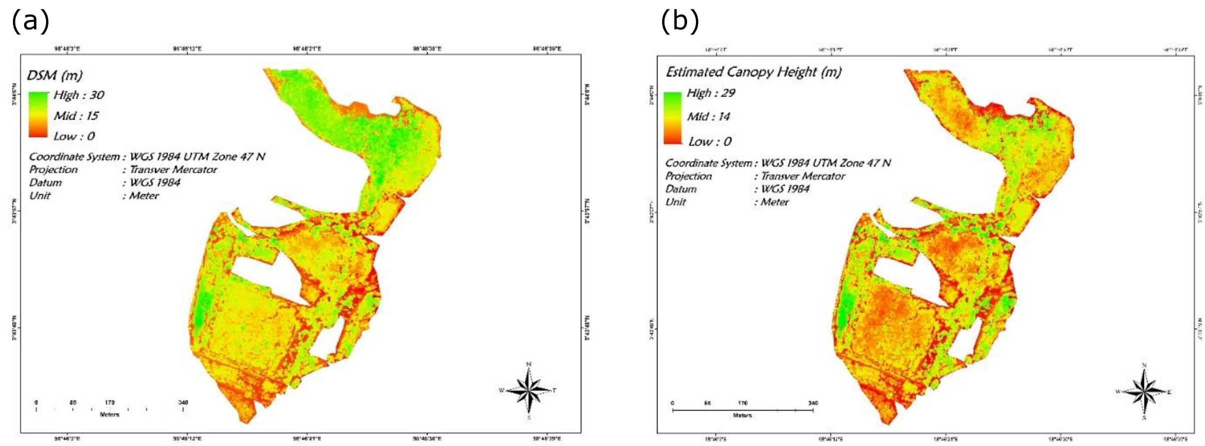


Figure 3. The Digital Surface Model (DSM) (a) and the height of the mangrove tree canopy in Tanjung Rejo (b).

The highest canopy is seen along the southwestern and northern edges, marked by a green color. The mangrove vegetation in the study area consists of dense mangrove forests. The tallest canopies are generally found in areas with dense mangroves, while the shorter canopies are located in more sparse mangrove areas, marked by red color. Canopy height measurements and Lorey's height estimates can provide more accurate and rich data to understand the health, structure, and dynamics of forest ecosystems.

LH is determined by the correlation between the mangrove canopy height and the tree height as seen in the field (Figure 4). In the case of Tanjung Rejo, the relationship between LH and mangrove height follows an exponential pattern, showing a robust coefficient of determination ($R^2$) of 0.93. This substantial $R^2$ indicates that the LH model is a reliable method for predicting the height of mangrove trees in the area. Therefore, the canopy height and LH values obtained from aerial imagery can be calculated using the equation below:

$$y = 1.0574x^{0.9384} \quad (5)$$

where: Y is the calculated LH and x is the calculated canopy height.

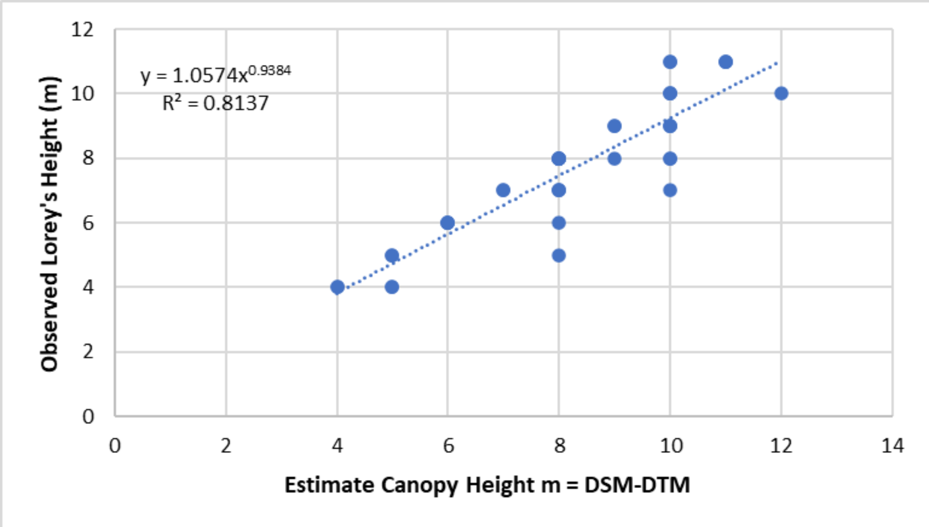


Figure 4. A scatter plot displaying the canopy height (DSM-DTM) alongside Lorey's height for the mangrove in Tanjung Rejo.

By utilizing equation (1), the calculation of LH, depicted in Figure 5, was obtained. The height distribution within the study region spans from 0 meters to 24 meters. The greatest values are concentrated along the southern-western and northern borders, which are highlighted in green. Conversely, the lowest measurements of LH, represented in red, are located in the southern zones of the study area, where the height is recorded as 0 meters.

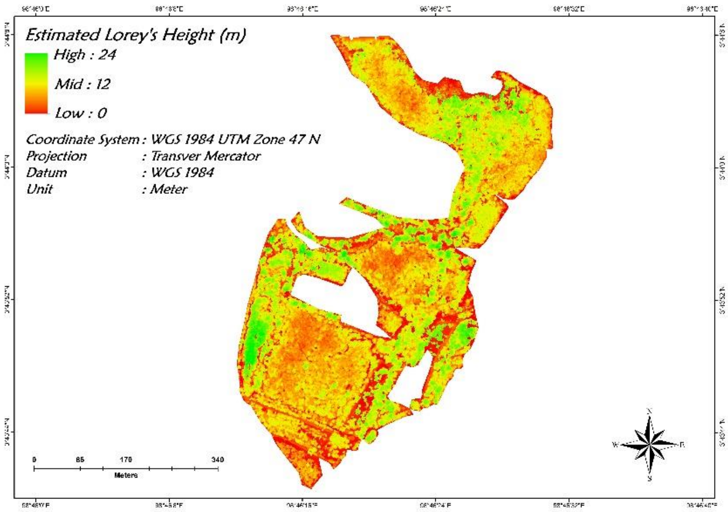


Figure 5. Estimation of Lorey's height of mangrove trees in Tanjung Rejo village.

***Above-ground biomass (AGB) and mangrove carbon stock***. To obtain the AGB results, the following equation was used:

$$\ln AGB\ (Mg\ ha^{-1}) = 0.81 + 1.81 \ln Hm \quad (6)$$

The findings from equation (6), illustrated in Figure 6, show that the mangrove AGB in Tanjung Rejo village varies between 9 and 758 Mg $ha^{-1}$. It is apparent that regions with greater LH values correspond to higher AGB biomass. In contrast, areas with lower LH values tend to have lower AGB biomass. This observation aligns with the research of Feldpausch et al (2012). The relationship between tree height and biomass is that taller trees tend to have larger trunk diameters and greater mass. As the height of the tree increases, the volume and mass of the trunk, branches, and leaves also continue to increase. Therefore, LH indicates that the area has many more large trees that store more biomass.

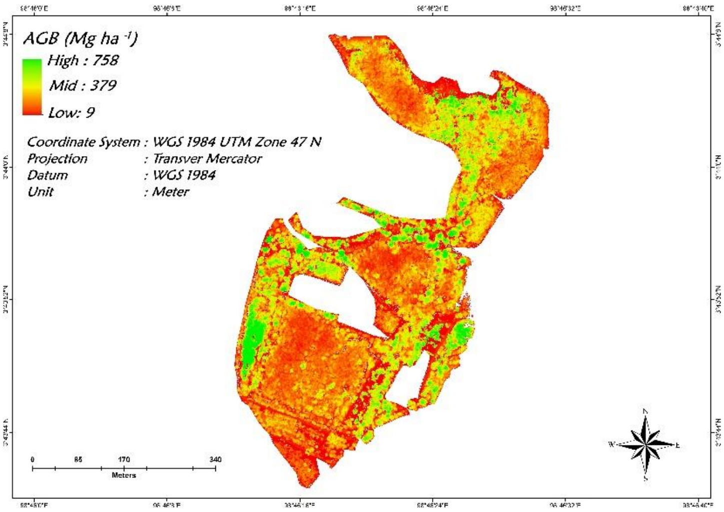


Figure 6. AGB mangrove map in Tanjung Rejo village.

Kuffman & Donato (2012) mentioned that the carbon content in mangrove wood is under 50%. As a result, a typical method for converting AGB to carbon biomass is by applying a factor of 0.5, which represents half of the AGB, to estimate the amount of carbon stored. The carbon biomass in Tanjung Rejo village is shown in Figure 7, with the figures indicating 50% of the mangrove AGB. The highest carbon stock in Tanjung Rejo village, which is situated in the Percut Sei Tuan District of Deli Serdang Regency, reaches 379 Mg ha$^{-1}$. The areas with the highest carbon stock potential are situated along the southwest and northern peripheries.

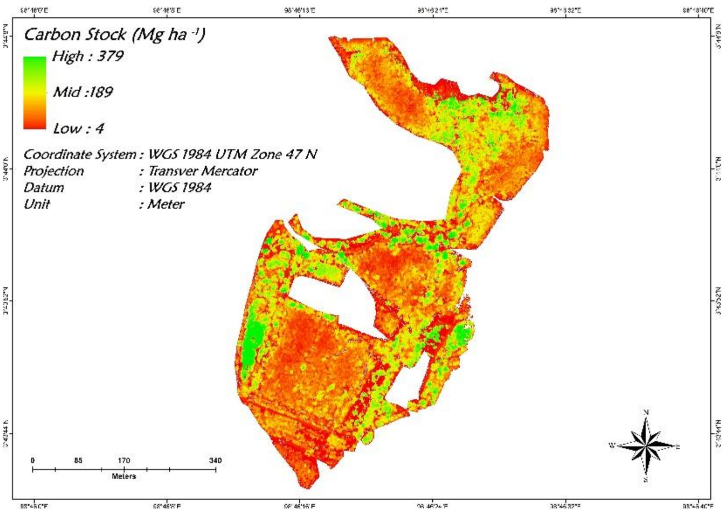


Figure 7. Carbon stock map.

**Discussion**. The carbon estimates obtained in this research are considerably higher when compared to earlier studies. According to Wirasatriya et al (2022), the mangrove biomass carbon stocks in the Karimunjawa-Kemujan Islands, assessed using UAV imagery, ranged from 8 to 328 Mg ha$^{-1}$, which is equivalent to 4 to 164 MgC ha$^{-1}$. In a separate study by Basyuni et al (2023), it was discovered that in Lubuk Kertang, the carbon stocks of mangrove biomass above ground varied from 0 to 173.8 Mg ha$^{-1}$, or 0 to 86.9 MgC ha$^{-1}$. On the other hand, research in Sembilan Island, Langkat, revealed carbon stock values ranging from 16 to 140.9 Mg ha$^{-1}$, or 8 to 70.5 MgC ha$^{-1}$. According to recent research by Thoha et al (2024), the restoration forest in Langkat District, Indonesia, holds significant potential for aboveground carbon storage with a value of 3,479.90 MgC. The high potential of biomass and above-ground carbon stocks within the mangrove ecosystem of Tanjung Rejo village is because the mangrove forest in this location is still in good condition and well-preserved.

Mangrove ecosystems play a crucial role in capturing organic carbon, leading to growing efforts focused on their restoration and preservation as a strategy for reducing greenhouse gas emissions (Sam et al 2023). Mangroves in Tanjung Rejo village not only play an essential part in addressing climate change by reducing carbon emissions storage but also provide significant ecosystem benefits (Samosir & Restu 2017). The high carbon stock indicates the great potential of mangrove forests as effective carbon sinks, reducing carbon dioxide concentrations within the environment, playing a role in managing global climate change. The importance of mangrove conservation and restoration as an essential approach for preserving the equilibrium of ecosystems and the surrounding area community welfare is emphasized (Samosir & Restu 2017).

The results also show that areas with the highest carbon stocks, such as the southwest and northern edges, tend to have better and denser mangrove conditions. This suggests that conservation and rehabilitation efforts should be focused on degraded areas to enhance carbon stocks across the region. Furthermore, the importance of education and raising awareness among local communities about the critical role of mangrove forests in carbon storage is stressed to guarantee the long-term viability of mangrove management in the future. This study aligns with previous findings that highlight the role of mangrove forests as one of the most important ecosystems for carbon storage, providing a strong evidence-driven foundation for creating conservation policies in the region that are both more efficient and long-lasting.

**Conclusions**. The highest mangrove vegetation canopy height in Tanjung Rejo village is 29 meters, located on the southwest and northern sides. The above-ground biomass and carbon estimation for mangroves in Tanjung Rejo village range from 9 to 758 Mg $ha^{-1}$ for above-ground biomass and 4 to 379 MgC $ha^{-1}$ for carbon stock estimation. With a study area of 21 hectares, the estimated carbon stored above the surface in the research area is estimated to be approximately 7,959 MgC. These findings highlight the significant carbon storage potential of mangrove ecosystems in Tanjung Rejo, underscoring their critical role in climate change mitigation. In the future, this data can serve as a valuable reference for implementing blue carbon initiatives, developing carbon credit schemes, and supporting conservation and restoration efforts. Moreover, integrating this research into coastal management policies could enhance the sustainable use of mangrove resources while contributing to regional and national climate targets.

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**Conflict of interest**. The authors declare that there is no conflict of interest.

## References

Aalde H., Gonzales P., Gytarsky M., Krug T., Kurz W. A., Ogle S., Raison J., Schoene D., Ravindranath N. H., Elhassan N. G., Heath L. S., Higuchi N., Kainja S., Matsumoto M., Sanchez M. J. S., Somogyi Z., Carle J. B., Murthy I. K., 2006 Forest land. In: 2006 IPCC guidelines for national greenhouse gas inventories. The Institute for Global Environmental Strategies (IGES), Hayama, Japan, 83 pp.

Akbar A. A., Sartohadi J., Djohan T. J. S., Ritohardoyo S., 2017 The role of breakwaters on the rehabilitation of coastal and mangrove forests in West Kalimantan, Indonesia. Ocean and Coastal Management 138:50-59.

Arinah H., Thoha A. S., Mardiyadi Z., Lubis O. A., 2021 Utilization of UAV (unmanned aerial vehicle) technology for mapping and identification of agroforestry land cover patterns in Namolandur village, North Sumatra. IOP Conference Series: Earth and Environmental Science 912(1):012075.

Basyuni M., Wirasatriya A., Iryanthony S. B., Amelia R., Slamet B., Sulistiyono N., Pribadi R., Sumarga E., Eddy S., Al Mustaniroh S. S., Sasmito S. D., Sidik F., Kajita T., Ali H. M., Macklin P. A., Arifanti V. B., 2023 Aboveground biomass and carbon stock estimation using UAV photogrammetry in Indonesian mangroves and other competing land uses. Ecological Informatics 77: 102227.

Feldpausch T. R., Lloyd J., Lewis S. L., Brienen R. J. W., Gloor M., et al, 2012 Tree height integrated into pantropical forest biomass estimates. Biogeosciences 9(8):3381-3403.

Harefa M. S., Nasution Z., Mulya M. B., Maksum A., 2022 Mangrove species diversity and carbon stock in silvofishery ponds in Deli Serdang District, North Sumatra, Indonesia. Biodiversitas 23(2):655-662.

Harris N. L., Gibbs D. A., Baccini A., Birdsey R. A., De Bruin S., Farina M., Fatoyinbo L., Hansen M. C., Herold M., Houghton R. A., Potapov P. V., Suarez D. R., Roman-Cuesta R. M., Saatchi S. S., Slay C. M., Turubanova S. A., Tyukavina A., 2021 Global maps of twenty-first century forest carbon fluxes. Nature Climate Change 11: 234-240.

Illarionova S., Shadrin D., Ignatiev V., Shayakhmetov S., Trekin A., Oseledets I., 2022 Estimation of the canopy height model from multispectral satellite imagery with convolutional neural networks. IEEE Access 10:34116-34132.

Kauffman J. B., Donato D. C., 2012 Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests. CIFOR, Bogor, 40 pp.

Maharani S., Bernard M., 2018 [Analysis of the relationship between mathematical resilience and students' problem-solving abilities on circle material]. Jurnal Pembelajaran Matematika Inovatif 1(5):819-826. [in Indonesian]

Mahmuda R., Aritonang D., Evitrisna E., Harefa M. S., 2023 [Addressing the rehabilitation of the mangrove area in Paluh Merbau, Tanjung Rejo, Deli Serdang Regency]. Humantech: Jurnal Ilmiah Multidisiplin Indonesia 2(3):553-565. [in Indonesian]

Nedhisa P. I., Tjahjaningrum I. T., 2020 [Estimation of biomass, carbon stock and carbon sequestration of mangroves in *Rhizophora mucronata* in Wonorejo Surabaya using allometric equations]. Jurnal Sains dan Seni 8(2):61-65. [in Indonesian]

Rudiyanto, Minasny B., Setiawan B. I., Saptomo S. K., McBratney A. B., 2018 Open digital mapping as a cost-effective method for mapping peat thickness and assessing the carbon stock of tropical peatlands. Geoderma 313:25-40.

Rull V., 2024 Origin and evolution of Caribbean mangroves: a time-continuum ecological approach. Ecological Studies (ECOLSTUD, volume 252). Cham: Springer Nature.

Sam K., Zabbey N., Gbaa N. D., Ezurike J. C., Okoro C. M., 2023 Towards a framework for mangrove restoration and conservation in Nigeria. Regional Studies in Marine Science 66:103154.

Sastra A. R., Putri D. N., Veranika A., 2023 [Vertical accuracy analysis of aerial photo DEM in residential areas (case study: Sekip Jaya village, Kemuning District, Palembang)]. Tekno Global Journal 12(1):41-46. [in Indonesian]

Samosir D. B., Restu R., 2017 [Analysis of the benefits of mangrove forests in Tanjung Rejo village, Sei Tuan District, Deli Serdang Regency, North Sumatra]. Geography Tunas Journal 6(1):1-15. [in Indonesian]

Sulaiman M., 2023 [Utilization of mangrove forests for handling climate change on Wetar Island]. Jurnal Kelautan dan Perikanan Terapan 1:67-71. [in Indonesian]

Sugiyono, 2015 [Combination research methods]. Alfabeta, Bandung, 630 pp. [in Indonesian]

Suryono S., Soenardjo N., Wibowo E., Ario R., Rozy E. F., 2018 [Estimation of biomass and carbon stocks in the mangrove forest of Perancak, Jembrana Regency, Bali Province]. Buletin Oseanografi Marina 7(1):1-8. [in Indonesian]

Suwa R., Rollon R., Sharma S., Yoshikai M., Albano G. M. G., Ono K., Adi N. S., Ati R. N. A., Kusumaningtyas M. A., Kepel T. L., Maliao R. J., Primavera-Tirol Y. H., Blanco A. C., Nadaoka K., 2020 Mangrove biomass estimation using canopy height and wood density in the South East and East Asian regions. Coastal and Shelf Science 248:106937.

Thoha A. S., Lubis O. A., Hulu D. L. N., Sari T. Y., Mardiyadi Z., 2022 Utilization of UAV technology for mapping of mangrove ecosystem at Belawan, Medan City, North Sumatera, Indonesia. IOP Conference Series: Earth and Environmental Science 977(1):012102.

Thoha A. S., Patana P., Hulu D. L. N., Adrianto H. A., 2024 Estimation of mangrove above-ground biomass and carbon stocks from unmanned aerial vehicle imagery in restoration forest, Langkat District, Indonesia. AACL Bioflux 17(3):1151-1160.

Wang C., Morgan G., Hodgson M. E., 2021 SUAS for 3D tree surveying: comparative experiments on a closed-canopy earthen dam. Forest 12(6):659.

Wirasatriya A., Pribadi R., Iryanthony S. B., Maslukah L., Sugianto D. N., Helmi M., Ananta R. R., Adi N. S., Kepel T. R., Ati R. N. A., Kusumaningtyas M. A., Suwa R., Ray R., Nakamura T., Nadaoka K., 2022 Mangrove above-ground biomass and carbon stock in the Karimunjawa-Kemujan Islands estimated from unmanned aerial vehicle-imagery. Sustainability 14(2):706.

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