# Estimation of mangrove above-ground biomass and carbon stocks from unmanned aerial vehicle-imagery in restoration forest, Langkat District, Indonesia

[1]Achmad S. Thoha, [1]Pindi Patana, [1]Dwi L. N. Hulu, [2]Hari A. Adrianto

[1] Faculty of Forestry, Universitas Sumatera Utara, Deli Serdang 20353, Indonesia;
[2] Computer Science Department, IPB University, Bogor 16680, Indonesia.
Corresponding author: A. S. Thoha, a.siddik@usu.ac.id

**Abstract**. The mangrove ecosystem can play a crucial role in carbon storage as it is one of the most carbon-dense ecosystems globally. The advancement of unmanned aerial vehicle (UAV) technology has the potential to aid in analyzing the carbon content of mangrove forests in a more detailed, cost-effective, and rapid manner. The restoration forest in Langkat District is still relatively extensive, with moderate to high density, requiring an assessment of the potential carbon reserves above its ground surface. This research aims to analyze the biomass potential and carbon reserves above the ground surface in mangrove forests using UAV technology. The primary data include aerial photographs captured by UAV, combined with digital surface model (DSM) and digital terrain model (DTM). Mangrove canopy height is calculated by subtracting DSM from DTM and converting it into Lorey's Height (LH). Field surveys were also conducted to measure the total tree canopy height and diameter at breast height to obtain LH, which was then converted into mangrove biomass. The highest canopy height of mangrove vegetation in Forest Restoration is 28 m, located on the northeast and south sides of the forest edge. The biomass potential above the ground surface and estimated carbon reserves of mangroves in restoration forest from UAV imagery ranged from 0 to 890 Mg ha$^{-1}$ and 0 to 445 MgC ha$^{-1}$, respectively. With a research area of 7.82 ha, the estimated carbon potential above the ground surface stored in the research area is approximately 3,479.90 MgC. The UAV technology in mangrove mapping especially in restoration forest provides opportunities for collecting very high-resolution spatial data on a small scale, ensuring accurate spatial data collection.

**Key Words**: above-ground biomass, carbon storage, carbon stock mapping, Unmanned Aerial Vehicle.

**Introduction**. Mangrove forests play an important role in carbon storage in the tropics. This mangrove function can help reduce carbon emissions and global warming (Nuraini et al 2021). Mangrove ecosystems can play a crucial role in carbon storage as one of the most carbon-dense ecosystems globally. This ecosystem can also function as a long-term carbon storage, capturing up to four times more carbon than other forests worldwide (Indra et al 2022). Increasing carbon reserves and carbon storage ecosystems, including mangrove ecosystems, are essential for achieving carbon emission reduction targets at both national and international levels.

The current mangrove restoration program by the Indonesian government aligns with remote sensing technology for mangrove mapping to support national emission reduction targets. The Indonesian government is currently participating in the FoLU (Forest and other Land Uses) Net Sink 2030 program for the forestry sector, aiming to achieve carbon absorption by 2030 (MoEF 2022). The goal of this program is to reduce carbon emissions from deforestation and forest degradation while enhancing carbon absorption and storage through reforestation and forest rehabilitation. The Indonesian government aims to revitalize 600,000 hectares of mangrove forest through the Peatland and Mangrove Restoration Agency (BRGM). To achieve the goals of mangrove forest rehabilitation and conservation, demonstrated by increased carbon reserves, this process must be monitored and assessed periodically.

Traditional mangrove biomass measurements were conducted by direct field measurements, including height, canopy/treetop area, and diameter at breast height (DBH). Measurement data in predetermined plots were then applied to allometric equations to obtain above-ground biomass (AGB) (Kauffmann & Donato 2012; Picard et al 2012). However, in-situ measurements can be challenging in dense mangrove stands or remote areas with limited access. These challenges result in poor survey coverage and measurement errors, ultimately leading to underestimations of measurable mangrove biomass (Jones et al 2020). Aboveground biomass measurements of mangrove forests are also made at the landscape scale using medium resolution satellite imagery (Bao & Hoa 2018).

Carbon stock mapping (CSM) is an effective way to understand how carbon storage is spatially distributed across the landscape. Mapping carbon stocks on a large scale is crucial for monitoring carbon storage and emissions dynamics (Harris et al 2021). Remote sensing techniques have been widely used to estimate carbon reserves in the past decade, both in mangrove forests (Jones et al 2020) and hill forests (Sivasankar et al 2019). A recent development is the rapid growth of unmanned aerial vehicles (UAVs) in overcoming the challenges of difficult access and high cost of survey work in mangrove forests. Unmanned aerial vehicle (UAV) technology provides advantages in capturing very high spatial resolution and more accurate data. Studies on the use of UAVs for mapping mangrove ecosystems in North Sumatra have been conducted by Thoha et al (2022a, b), where UAVs can provide detailed data on land use types and mangrove species mapping. Studies by Wirasatriya et al (2022) and Basyuni et al (2023) have developed UAV applications and allometric equations in mangrove areas in Java and Sumatera, Indonesia, for biomass estimation and above-ground carbon reserves.

Estimating carbon reserves in mangrove forests is required as a reference to support carbon emission reduction policies. Remote sensing technology for large-scale digital mapping can be conducted using open-source data in mapping mangrove forests and estimating carbon reserves in Indonesian mangrove forests. Open-source data provides a good balance between accuracy, cost, and time (Rudiyanto et al 2018). The objective of this research is to analyze the potential above-ground carbon reserves from UAV imagery.

## Material and Method

***Description of the study sites***. The research was conducted in restoration forest of Lubuk Kasih Village, Brandan Barat District, Langkat Regency, North Sumatera (Figure 1). The research area, delineated during the study, covers 7.82 hectares. The research was conducted from August 2023 to February 2024. The UAV images used in the study were acquired through aerial data collection conducted by the researchers in September 2023. Image analysis and estimation of AGB and carbon reserves were carried out at the Forest Resource Conservation Laboratory, Faculty of Forestry, Universitas Sumatera Utara.

***Materials and data***. The equipment used for field data collection and UAV image acquisition, along with their applications, included the DJI Mavic 2 Pro quad-copter UAV. Other tools used were a Personal Computer, DJI Go 4, Pix4Dcapture software, Avenza Maps, Agisoft Metashape Professional (64-bit), PCI Geomatica, a Haga meter, and writing materials. The research data consisted of aerial photo images taken during the UAV mission, as well as data from mangrove tree height and diameter measurements.

Primary data were obtained through aerial photo acquisition using a UAV conducted directly in restoration forest. Aerial photos were taken by first creating a mapping mission using the DJI Mavic 2 Pro drone and the Pix4D application.

***Aerial photo data processing***. Aerial photos taken during the UAV flight mission undergo the following processing steps: align photos, build dense cloud, build mesh, build texture, build digital elevation model (DEM), and build orthomosaic. The orthomosaic image was stored in GeoTIFF format, and the DEM was then processed through digital terrain model (DTM) processing using PCI Geomatica software.

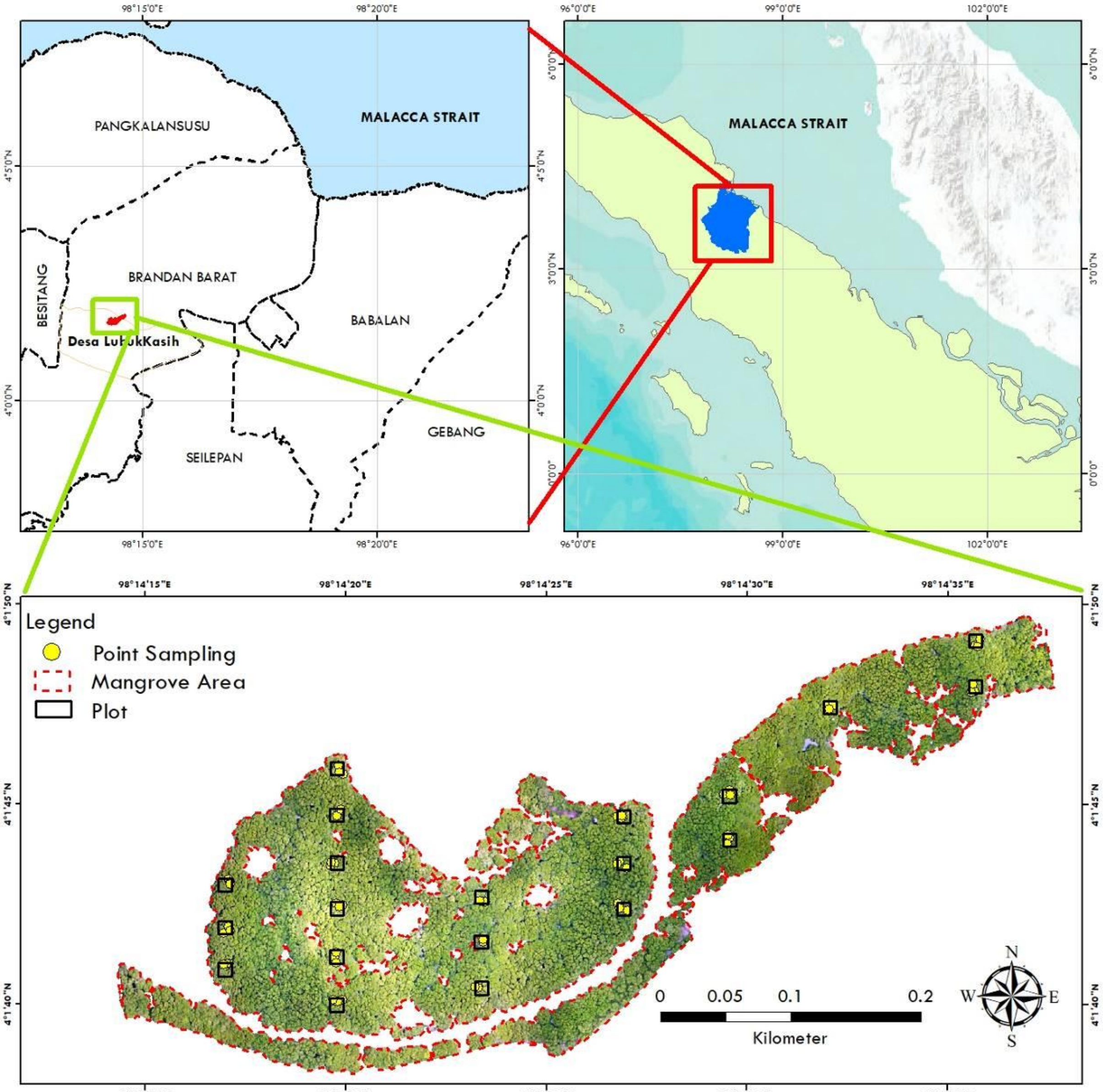

Figure 1. The study area in Brandan Barat District, Langkat Regency, North Sumatera.

***Mangrove survey*.** Height and DBH measurements were conducted on selected trees within the sample plots. The selection of points for the mangrove survey is crucial. Since the accuracy of the handheld global positioning system (GPS) for mangrove surveys was significantly lower than the global navigation satellite system (GNSS) used for UAV photogrammetry reference, we chose trees with the most dominant canopy in each plot to reduce the possibility of mismatched points between handheld GPS and UAV image GPS. Subsequently, arithmetic height was converted into Lorey's Height (LH) to estimate mangrove biomass from tree height. LH is the weighted average height where each tree is weighed proportionally to its basal area. The calculation of LH is based on formula 1 and formula 2 (Simard et al 2019; Suwa et al 2021) as follows:

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

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

where: Hm, H, and BA respectively represent LH, arithmetic height, and basal area. Subsequently, the LH obtained from tree sampling points in the field was used to create an algorithm for calculating canopy height from aerial photos.

Canopy height model (CHM) is the height of the vegetation canopy from the ground surface in its vicinity. CHM data are useful for analyzing forest characteristics, such as estimating wood stocks and measuring forest growth (Illarionova et al 2022). DTM was then subtracted from digital surface model (DSM) to obtain the CHM for the study location (Matese et al 2017). CHM was calculated using the following formula (formula 3):

Canopy Height Model (CHM) = DSM-DTM (3)

***Calculation of above-ground biomass***. To estimate mangrove AGB, we used the Lorey's mean canopy height Hm-AGB relationship generated for the Southeast Asia and East Asia regions (Suwa et al 2021) as follows (formula 4):

AGB = 0.81 + 1.81 lnHm (4)

The height index used in this study is LH, which is the height weighted by the basal area of all trees. Stand biomass (Mg ha$^{-1}$) depends primarily on large canopy and taller trees, and LH can be a good proxy for estimating stand biomass. Carbon above-ground or above-ground carbon biomass is half of AGB (IPCC 2006).

## Results

***Tree canopy height and Lorey's Height estimates***. Based on the calculation of mangrove area height using the DSM, the elevation in the mangrove area at the research location ranges from 0 m to 32 m (Figure 2a). The 0-meter elevation represents areas without vegetation or riverbeds. The elevation of the mangrove area in forest restoration, including regions with gentle slopes, ranges from 0 to 4 m. Therefore, the obtained canopy height of trees ranges from 0 m to 28 m (Figure 2b). The tallest canopies were observed along the southern, eastern, and northeastern edges, marked by a visual representation in red. The mangrove vegetation in the research location was dense. Taller canopies were generally found in dense mangrove conditions, while lower canopies were present in sparser mangrove areas. According to interviews with the local government of Lubuk Kasih Village, the mangrove area in the study location was largely a result of a forest rehabilitation program in 2009, estimating the age of the mangrove trees to be around 15 years. LH estimate is the relationship between the height of mangrove tree canopies and the height of trees observed in the field (Figure 3). The analysis of mangrove LH in restoration forest follows a power pattern with a relatively high coefficient of determination ($R^2$), which is 0.75. The sufficiently high $R^2$ value indicates that the LH equation is reliable in estimating the height of mangrove trees in restoration forest. Thus, the conversion of calculated canopy height into LH height from aerial photos can be done using the following equation (formula 5):

y = 1.0232x0.9756 (5)

where: Y is LH, and x is canopy height (CHM).

By applying formula 5 to the height distribution (Figure 3), the LH results were obtained (Figure 4). The distribution of LH in the study location ranges from 0 m to 27 m. The highest distribution was observed along the southern, eastern, and northeastern edges. The LH of mangrove trees reaches up to 13 m in the central-western part, distant from Paluh, while the central-northern part represents the area with the minimum LH height ranging from 0 to 13 m.

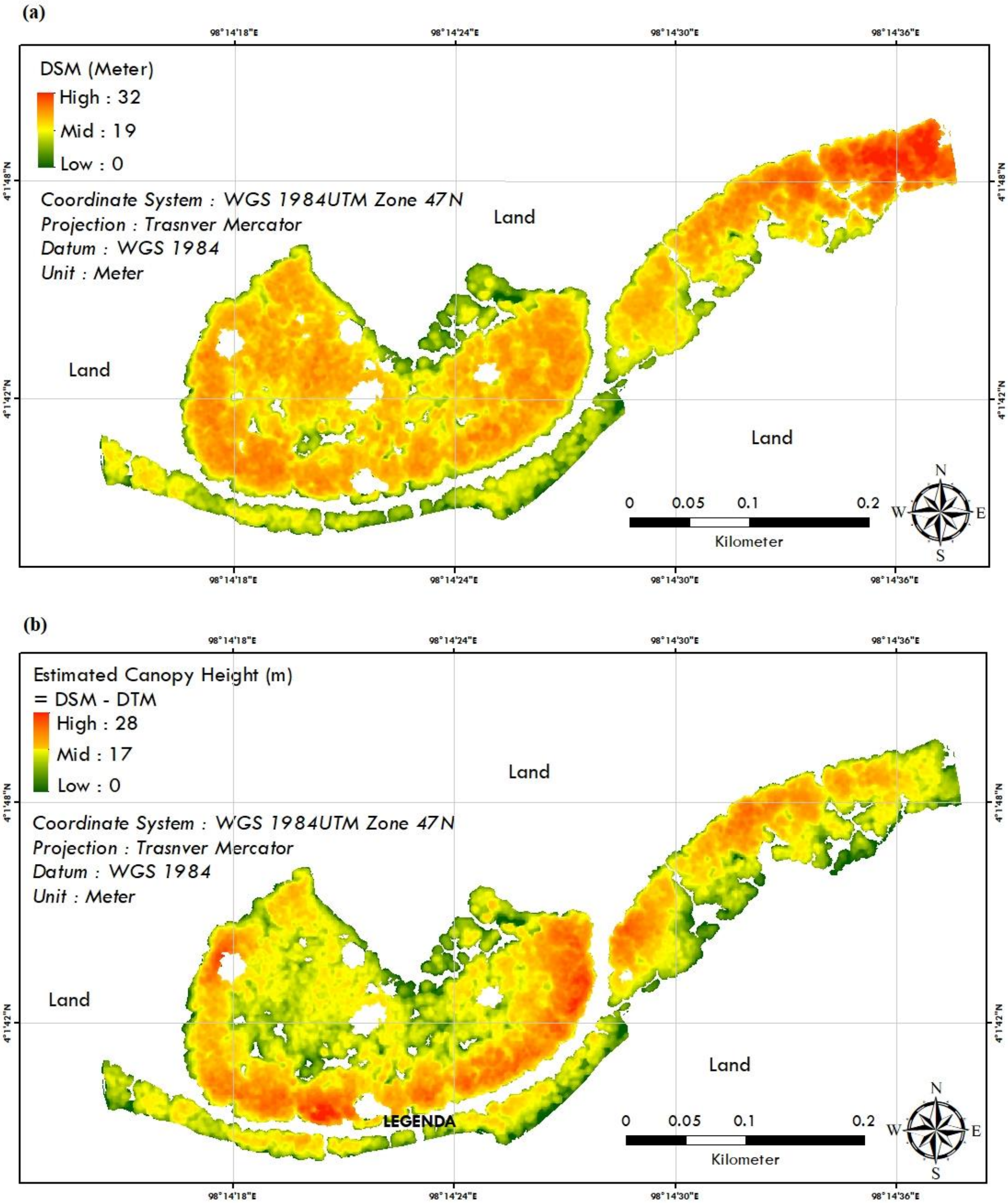

Figure 2. Digital surface model DSM (a), and mangrove tree canopy height in restoration forest (b).

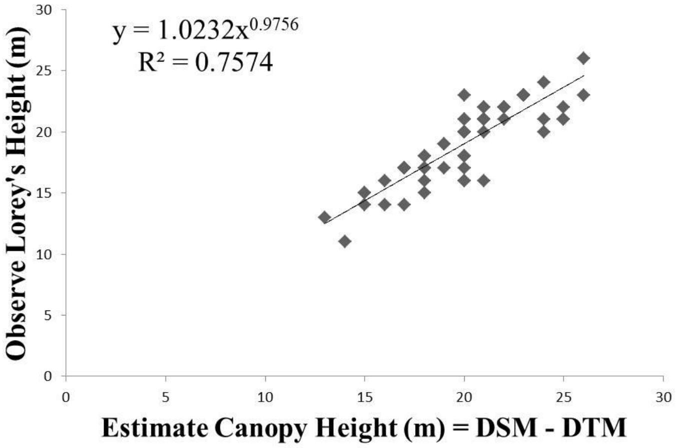

Figure 3. Scatter plot of canopy height (DSM-DTM) and Lorey's Height of mangrove restoration forest.

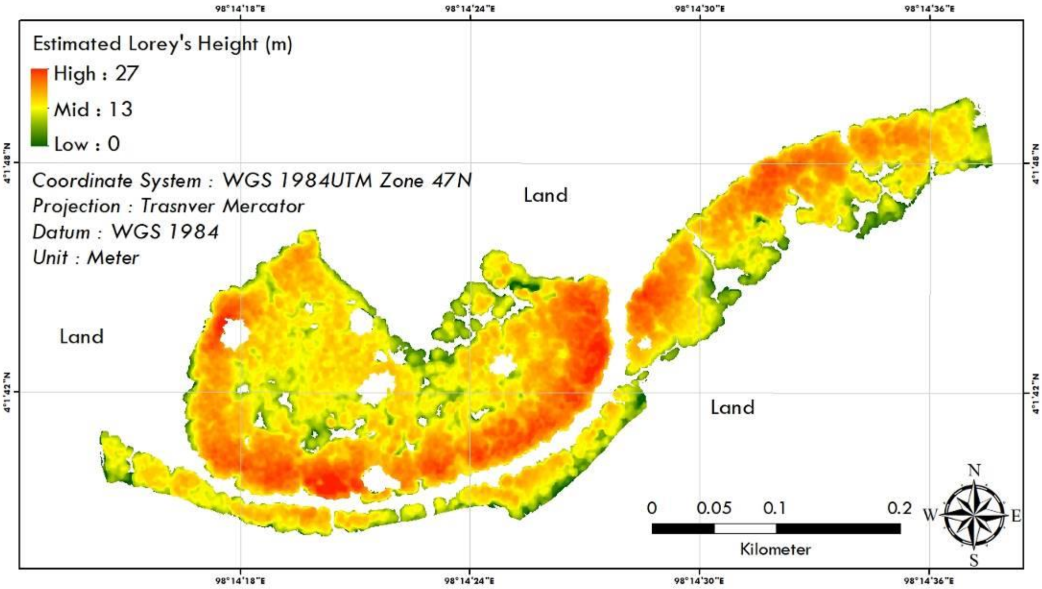

Figure 4. Estimated Lorey's Height of mangrove trees in Lubuk Kasih.

***Aboveground biomass and carbon stocks of mangrove***. To obtain AGB results, the equation in formula 6 applied in the study by Suwa et al (2021) can be used:

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

Based on the results of equation 6 visualized in Figure 5, the AGB of mangroves in Lubuk Kasih ranges from 0 Mg ha$^{-1}$ to 890 Mg ha$^{-1}$. Areas with high LH values have high biomass, while areas with low biomass are associated with trees having low LH values. In this study, carbon stock estimates use a multiplication factor of 0.5 or 50% of AGB to convert it into carbon stock. Carbon biomass in restoration forest is presented in Figure 6 with values equal to half of the mangrove AGB. The highest carbon stock in mangroves restoration forest is 445 MgC ha$^{-1}$. The highest potential for carbon stock is located all edges of mangrove restoration forest area.

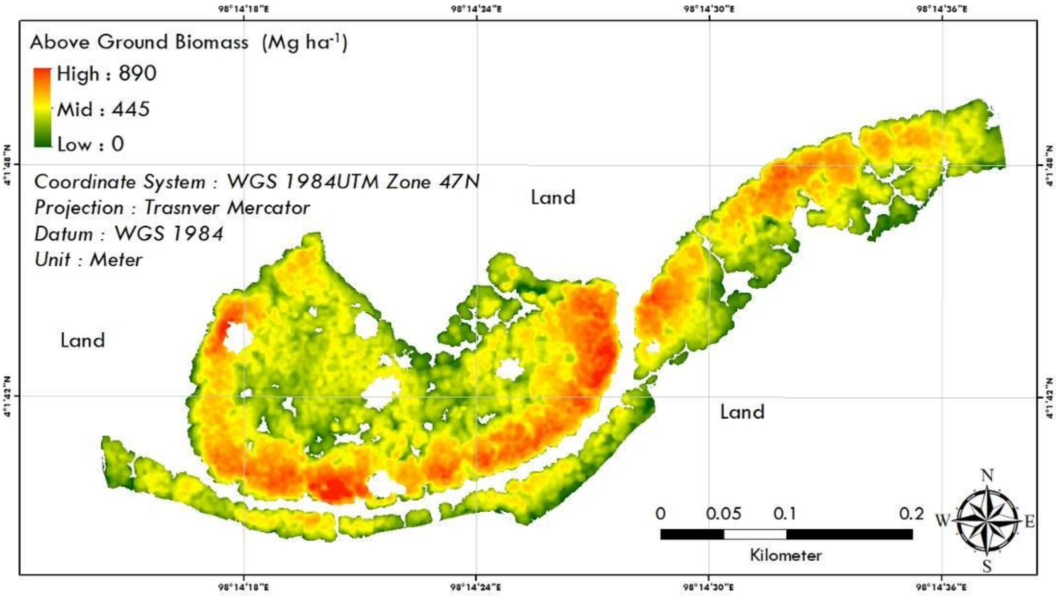

Figure 5. The distribution above-ground biomass of mangroves restoration forest.

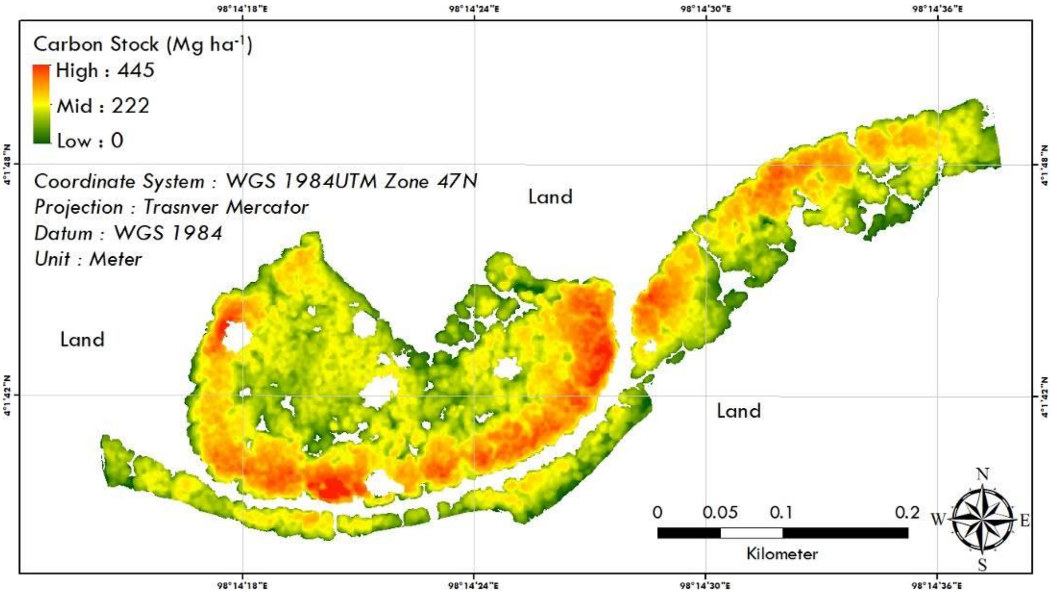

Figure 6. The distribution above-ground carbon stock of mangroves restoration forest. The value of aboveground carbon stocks is 50% of aboveground biomass.

**Discussion**. The carbon estimation results from this study were relatively higher compared to other mangrove ecosystem locations. A study using a similar method by Wirasatriya et al (2022) found that carbon stock estimates of AGB in the Karimunjawa-Kemujan Islands using UAV imagery ranged from 8 to 328 Mg ha$^{-1}$ and from 4 to 164 MgC ha$^{-1}$. Meanwhile, Basyuni et al (2023) calculated aboveground carbon stocks of mangrove in restoration forest of Lubuk Kertang and they found that the range of 0-173.8 Mg ha$^{-1}$ and 0-86.9 MgC ha$^{-1}$. In Pulau Sembilan Langkat, Basyuni et al (2023) also found that aboveground carbon stocks of mangrove ranges were 16-140.9 MgC ha$^{-1}$ and 8-70.5 MgC ha$^{-1}$. The results of the calculation of mangrove carbon stocks by Kepel et al (2017) found carbon stocks in Kema North Sulawesi amounted to 133.76±25.70 MgC ha$^{-1}$.

The high biomass potential and carbon stock above the ground in restoration forest are due to the well-preserved mangrove forest in this location. Field surveys revealed numerous and densely packed trees reaching a height of 28 m. The mangroves in the research location were planted in 2009 and are all of the *Rhizophora mucronata* species.

The estimated AGB in mangroves was higher compared to other land uses such as oil palm. A study by Basyuni et al (2023) found that carbon stock potential in oil palm land in Lubuk Kertang, North Sumatera, was 0.7-6.7 MgC ha$^{-1}$, and 0-5.5 MgC ha$^{-1}$ in Pulau Sembilan. Another study found that mature oil palm carbon stocks in Tanjung Puting, West Kalimantan, were 12 MgC ha$^{-1}$ (Novita et al 2021). A study by Khasanah et al (2015) stated that oil palm carbon reserves were much lower compared to the average carbon reserve of oil palm plantations growing on mineral soil (38.78 MgC ha$^{-1}$) and peat soil (37.3 MgC ha$^{-1}$) in Indonesia.

The estimation of carbon stock distribution in this study shows the potential for using UAV mapping techniques for broader implementation in Indonesia, especially for mangrove forests. This technological development allows cost efficiency for specific units of area (Otto et al 2018), and tree dimension measurements could require less field time (McCann et al 2022). UAV technology in mangrove mapping provides opportunities for collecting very high-resolution spatial data on a small scale and accurate spatial data collection, which can enhance greenhouse gas emission estimates and carbon absorption. However, remote sensing information on forest changes is not often integrated into remote sensing systems, and UAV applications have not yet become standard in land-use change monitoring. Therefore, the implementation of UAVs in monitoring and assessing mangrove ecosystems has the potential for widespread use and may become a focus of future research.

**Conclusions**. The highest canopy height of mangrove vegetation in restoration forest was 28 m, located on the northeastern and southern sides at the forest edge. The estimates of above-ground biomass and carbon stock in mangroves restoration forest range fromd 0 to 890 Mg ha$^{-1}$ and from 0 to 445 MgC ha$^{-1}$ respectively. With a study area of 7.82 ha, the potential carbon stock above the ground stored in the study area was estimated to reach 3,479.90 MgC. The carbon stock potential in restoration forest is higher compared to research using the same method in other mangrove ecosystems in different locations in Indonesia.

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

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Authors:
Achmad Siddik Thoha, Faculty of Forestry, Universitas Sumatera Utara, Deli Serdang 20353, Indonesia, e-mail: a.siddik@usu.ac.id
Pindi Patana, Faculty of Forestry, Universitas Sumatera Utara, Deli Serdang 20353, Indonesia, e-mail: pindi@usu.ac.id
Dwi Lestari Nalai Hulu, Faculty of Forestry, Universitas Sumatera Utara, Deli Serdang 20353, Indonesia, e-mail: hulunalai@gmail.com
Hari Agung Adrianto, Computer Science Department, IPB University, Bogor 16680, Indonesia, e-mail: agung@apps.ipb.ac.id

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