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Short Communication: Mangrove area and mangrove carbon stock in the coastal city of Banda Aceh, Indonesia

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Abstract. *Dharma W, Pratiwi A, Rasnovi S, Sutekad D, Fauzi R. 2025. Short Communication: Mangrove area and mangrove carbon stock in the coastal city of Banda Aceh, Indonesia. Biodiversitas 26: 1582-1589.* Climate change or global warming refers to the increase in Earth's average surface temperature due to the greenhouse effect, with CO_2 being one of the primary contributors. This has caused global temperatures to rise, significantly altering weather patterns, melting polar ice caps, and rising sea levels, which impacts the environment and public health. To mitigate carbon dioxide levels in the atmosphere, it is essential to enhance carbon absorption by utilizing mangrove vegetation. This study aims to assess the extent of mangrove areas in four sub-districts of Banda Aceh City and determine the associated mangrove carbon stocks. The research method employed the ArcGIS 10.8 software using Sentinel-2A satellite imagery (surface reflectance), accessed through the Google Earth Engine (GEE) platform, to calculate mangrove areas and carbon stocks. The results indicate that the Kuta Raja Sub-district has the largest mangrove area of 93.7531 ha, followed by Syiah Kuala (75.4098 ha), Kuta Alam (50.6548 ha), and Meuraxa (41.9272 ha). Regarding mangrove carbon stocks, the Kuta Alam Sub-district exhibits the highest carbon stock value in high-density class, ranging from 15.99 to 40.78 t C ha^{-1}, followed by Kuta Raja (18.50-38.97 t C ha^{-1}), Meuraxa (11.07-34.00 t C ha^{-1}) and Syiah Kuala (9.71-28.43 t C ha^{-1}).

Keywords: Carbon stocks, global warming, mangroves, remote sensing, satellite imagery

Abbreviations: AGB: Above Ground Biomass; BGB: Below Ground Biomass; GEE: Google Earth Engine; NDVI: Normalized Difference Vegetation Index; TAB: Total Accumulated Biomass; TCS: Total Carbon Stock

INTRODUCTION

Global warming is one of the most pressing issues associated with climate change. It refers to the rise in the Earth's temperature due to the trapping of long-wave radiation by greenhouse gases, such as CO_2, CFC, N_2O, CH_4, and O_3. Among these, CO_2 is the most influential, accounting for 50% of the total greenhouse gases (Bindu et al. 2020). A key mitigation strategy to reduce global warming caused by greenhouse gases is to enhance the role of mangroves as carbon sinks and storage systems (Ash et al. 2024). Mangrove ecosystems, which are found in coastal areas, are more effective at sequestering carbon than other ecosystems, including tropical rainforests (Maulidia et al. 2022; Zhu and Yan 2022). CO_2 from the atmosphere is absorbed through photosynthesis, and the biomass stored in mangrove vegetation represents their carbon stock potential (Sahu and Kathiresan 2019; Erniasari et al. 2024; Sugiana et al. 2024). Globally, mangrove forests account for only 0.4% of the world's total forest area. However, according to the 2021 update from Central Statistics Agency, Indonesia is home to 3.3 million hectares of mangrove forests, representing 23% of the world's total mangrove area (Giri et al. 2011). In Aceh Province, based on BPS Aceh (2015), the mangrove area was recorded at 58,925.50 hectares. Mangrove forests provide numerous benefits, including serving as food sources, wildlife habitats, shoreline protection, and as sinks and stores for CO_2, due to their higher rate of photosynthesis compared to other types of forests (Hastuti et al. 2018).

The existence of urban mangrove forests potentially contributes to mitigating the environmental problems (Sumarga et al. 2023). The development of urban forests in Banda Aceh is expected to create environmental sustainability in urban areas (Dharma et al. 2024). In Banda Aceh City, the potential for mangrove ecosystems is distributed across several regions, including Syiah Kuala, Kuta Alam, Kuta Radja, and Meuraxa Sub-districts (Gogo et al. 2022). Before the 2004 Tsunami, mangrove forests grew naturally along the coastline, preserving the ecosystem. However, the Tsunami caused significant damage to mangrove forests, so replanting was carried out while maintaining existing mangrove species (Affan et al. 2019). This situation highlights the need to assess carbon stocks in the city's mangrove areas. The measurement of carbon stocks in mangroves can be accomplished through the utilization of a remote sensing approach (Rafdinal et al. 2022) and ArcGIS for analysis (Nesperos et al. 2021), utilizing cloud-based data from the Google Earth Engine (GEE) (Sharma et al. 2024).

Traditional field-based measurement techniques are the most accurate for collecting biomass data (Lu 2006). However, these methods can be time-consuming and difficult to implement, especially in remote areas where biomass distribution over large regions cannot be easily quantified (Goswami et al. 2024). In contrast, remote sensing offers an effective solution, allowing for large-area coverage, cost efficiency, and periodic monitoring (Hendrawan et al. 2018). Remote sensing technology can also estimate the potential of mangrove vegetation to act as a CO_2 sink, offering an efficient and effective means of monitoring these ecosystems (Patil et al. 2015).

Research on estimating carbon stocks stored in mangrove vegetation is critical for understanding the capacity of mangrove forests to absorb and store carbon, thereby supporting sustainable management practices that help mitigate global warming (Basyuni et al. 2024). Situmorang et al. (2016) found a high correlation (R^2) = 0.728 between vegetation indices derived from satellite data and carbon stock estimation based on an allometric equation. This strong correlation indicates that satellite data is a reliable tool for estimating carbon stocks. Many studies have utilized remote sensing techniques to measure carbon stocks in mangrove vegetation (Hastuti et al. 2018; Anand et al. 2020; Bindu et al. 2020). Thus, this study aims to assess the extent of mangrove areas and mangrove carbon stocks in Banda Aceh City, contributing to data for global warming mitigation and conservation efforts.

MATERIALS AND METHODS

Study area

This research was conducted from June to August 2024. The study areas included Syiah Kuala, Kuta Alam, Kuta Raja, and Meuraxa Sub-districts in Banda Aceh City (Figure 1). Banda Aceh, the capital and largest city of Aceh province, Indonesia, is located at the western tip of Sumatra Island and covers an area of approximately 61.36 Km^2. The city topography is relatively flat, with slopes ranging between 2 to 8%. Approximately 70% of Banda Aceh's area is less than 5 meters above sea level (Dharma and Zakaria 2022). Banda Aceh is divided into nine Sub-districts, four directly adjacent to the coast, where mangrove vegetation is distributed.

Procedures

The process starts with data collection, proceeds to the interpretation of the data, and concludes with the presentation results. Data was processed using the ArcGIS 10.8. Mangrove carbon stocks in four sub-districts of Banda Aceh City, including Syiah Kuala, Kuta Alam, Kuta Raja, and Meuraxa, were analyzed using Sentinel-2A satellite imagery with a spatial resolution of 10 meters. Park et al. (2017) The imagery produced by the Sentinel-2A satellite has spatial resolutions of 10, 20, and 60 m. The specific bands used for the analysis were band 4 (Red), band 8 (SWIR), and band 11 (NIR), which were downloaded from the Google Earth Engine (GEE) platform.

The interpretation results of the mangrove distribution pattern in Negeri Passo using the combination of bands 8-11-4 (Near Infrared, Shortwave Infrared, Red) clearly distinguish the delineation of mangroves from forest vegetation delineation (Pietersz et al. 2024). The images selected for the study were captured between January 1, 2023, and December 31, 2023; the data has undergone atmospheric, geometric, and radiometric corrections that were automated through pre-processing by GEE. Then, image processing and making composite images, where band composites were created to enhance mangrove areas visually, making it easier to distinguish mangroves from other types of vegetation.

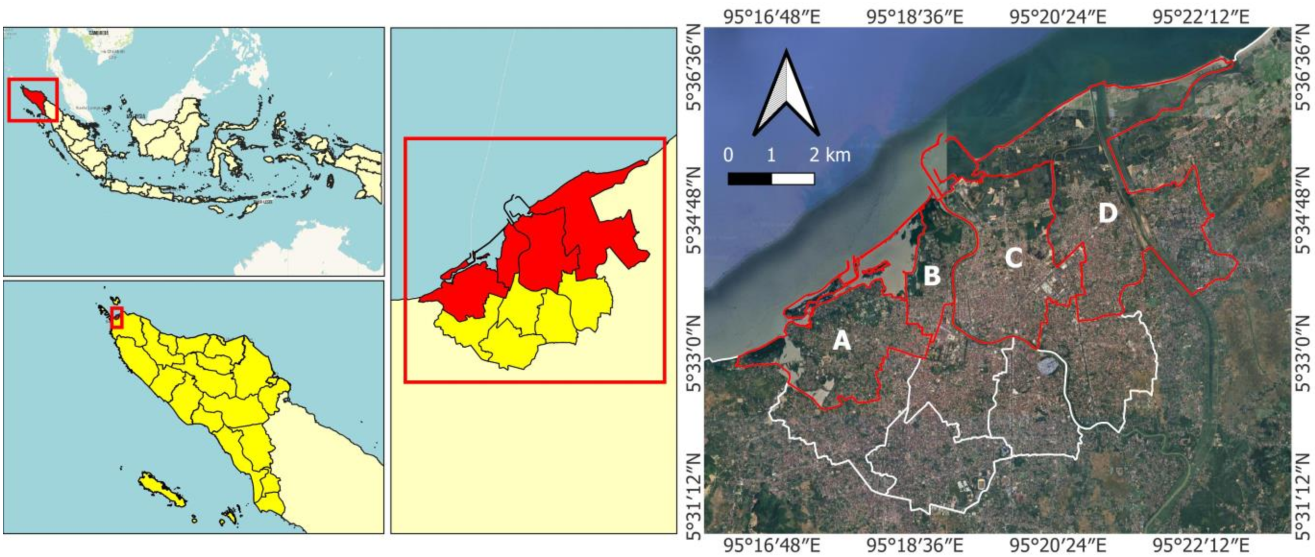

Figure 1. The geographic location of research areas: A. Meuraxa; B. Kuta Raja; C. Kuta Alam; and D. Syiah Kuala Sub-districts, Banda Aceh City, Aceh Province, Indonesia

Based on these spectral differences, area classification was carried out using the guided classification method (iso-cluster unsupervised classification). The ISODATA clustering technique, an unsupervised classification method, was applied to 61 Landsat images. Statistical analysis indicated that the total mangrove forest cover was approximately 256,185 hectares around 2000, with an overall classification accuracy of 96.6% and a kappa coefficient of 0.926 (Long and Giri 2011). The guided classification separated the complex area into simpler classes. After this stage, the ground check will be conducted. The raster data from the unsupervised analysis was verified through field checks after being compared with reference data from Google Earth to ensure the accuracy of mangrove classification. Semedi et al. (2023) conducted an accuracy assessment by comparing sample points on high-resolution imagery from Google Earth Pro to evaluate the accuracy of mangrove classification. Following this, the data is converted from raster to vector format, and calculations of mangrove area and mangrove carbon sequestration stocks will be conducted.

Data analysis

The analysis of mangrove carbon stock and sequestration was conducted using ArcGIS 10.8 (Hastuti et al. 2018). The analysis follows a systematic approach using vegetation indices, above-ground biomass estimation, below-ground biomass estimation, total biomass accumulation, total carbon stock calculations, and CO_2 sequestration assessments.

Vegetation index

The vegetation index was calculated using the Normalized Difference Vegetation Index (NDVI). NDVI measures the visible and near-infrared light reflected by vegetation. The NDVI is a measure of vegetation and represents the photosynthetic activity in an area (Smith et al. 2017). The pixel value classification for NDVI ranges from -1 to 1. Low (negative) NDVI values indicate areas such as water bodies, rocks, sand, and snow, while high (positive) values correspond to vegetated areas like savannah, shrubs and forests. NDVI values close to 0 typically represent barren land. The NDVI algorithm used is as follows (Huang et al. 2021):

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

Where :
NIR : Near Infrared band
RED : Red band

NIR reflectance (band 8) which has a center wavelength of 842 nm is influenced by the leaf's internal structure and dry matter content, while Red (band 4) reflectance corresponds to the visible wavelength at 665 nm and is represented by band 3 in ETM+ images. NDVI images are generated to enhance mangrove forests, which show higher NIR reflectance and lower red light reflectance. These images are also adjusted to exclude water bodies, low red light reflectance, and very low NIR reflectance.

Above Ground Biomass (AGB) estimation

The correlation result of the NDVI value equation with mangrove AGB is 0.787 (Jha et al. 2015), the formula for estimating the value of land surface biomass is as follows (Myeong et al. 2006):

$$AGB = 305.9 * NDVI^{4.864}$$

Where :
NDVI : Vegetation Index value
AGB : Above Ground Biomass value (t ha^{-1})

Below Ground Biomass (BGB) estimation

The estimation of Below-Ground Biomass (BGB) is derived from the AGB estimation using the following equation (Cairns et al. 1997):

$$BGB = Exp(-1.0587+0.8836*Ln(AGB))$$

Where :
AGB : Above Ground Biomass value (t ha^{-1})
BGB : Below Ground Biomass value (t ha^{-1})

Calculation of Total Accumulated Biomass (TAB)

Total Accumulated Biomass (TAB) is calculated by summing the AGB and BGB values (Hogarth 2002):

$$TAB = AGB + BGB$$

Where : TAB is Total Biomass Accumulation (t ha^{-1})

Calculation of Total Carbon Stock (TCS)

Total Carbon Stock (TCS) is calculated using the formula (Westlake 1963):

$$TCS = TAB * \%C\ Organic$$

Where :
TCS : Total Carbon Stock value (t C ha^{-1})
TAB : Total Biomass Accumulation value (t ha^{-1})
%C organic : Organic carbon percentage value (0,47), carbon deposits are estimated from 46% of biomass (Dewanti et al. 2020)

RESULTS AND DISCUSSION

Mangrove Areas

The Red, Green, and Blue (RGB) image composite processing results using the NIR, SWIR, and Red band showed different color combinations; mangroves were marked in dark orange, water bodies in dark blue, non-mangrove vegetation in yellow, and non-vegetation areas in light blue (Figure 2).

Based on these spectral differences, area classification was carried out using the guided classification method (iso-cluster unsupervised classification). The classification results still produce bias (Figure 3). In some cases, areas not covered by mangrove vegetation were erroneously identified as mangrove areas. The misclassified areas were then removed using the edit vertices toolbar in ArcGIS, ensuring that the final classification accurately represented mangrove vegetation (Figure 4).

Field checks were carried out from the classification results using the mangrove area and coordinate points. From 12 location points, 1 location was obtained that was not a mangrove area, so the percentage of validation suitability in the field was 91.66%. According to McCoy (2005), the accuracy level of the interpretation results that can be used for further analysis is at least 80-85%. This shows that the percentage of validation in the field can be used for further analysis.

Banda Aceh City's mangrove areas have been rehabilitated since the 2004 Tsunami. As shown in Figure 4, the distribution of mangroves varies across the four sub-districts, likely due to differences in the size of the areas and their proximity to the coast. This variation can also be attributed to the present of water flow in the regions, such as rivers and community ponds, where mangroves thrive. According to Niagara et al. (2021) and Sudhir et al. (2022), mangroves typically live along coasts, rivers, and estuaries in tropical and subtropical regions, with roots adapted to muddy, saline, or brackish environments. Mangroves can occur in areas with salinity ranging from 11 to 25% and can grow in shallow waters due to their specialized root structures (Niagara et al. 2021; Waleed et al. 2025).

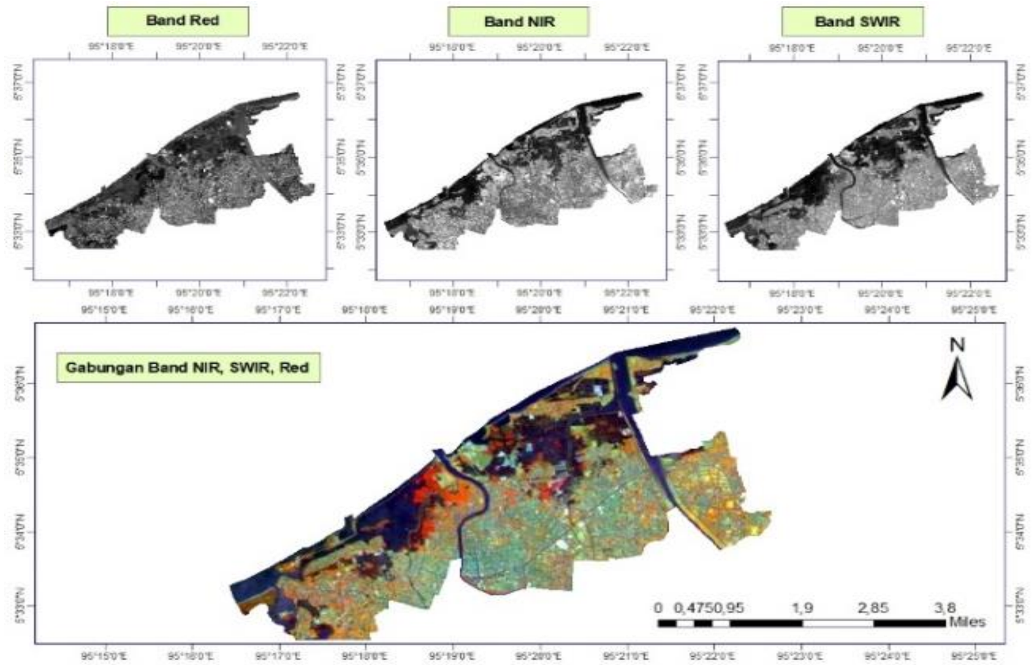

Figure 2. Band combination for observing mangrove areas in Banda Aceh City, Aceh Province, Indonesia

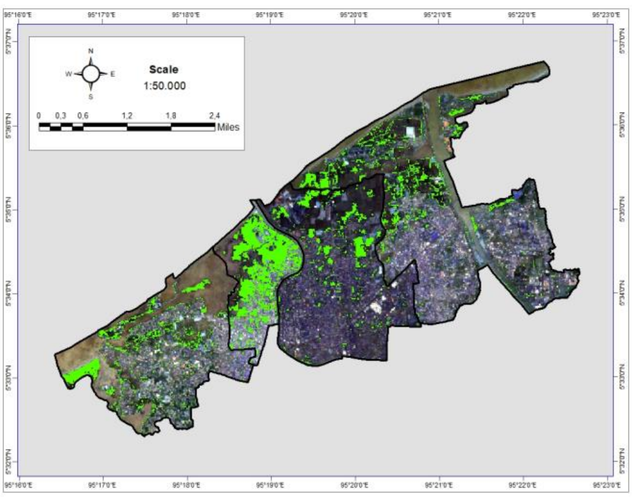

Figure 3. Results of unsupervised classification in Banda Aceh City, Aceh Province, Indonesia

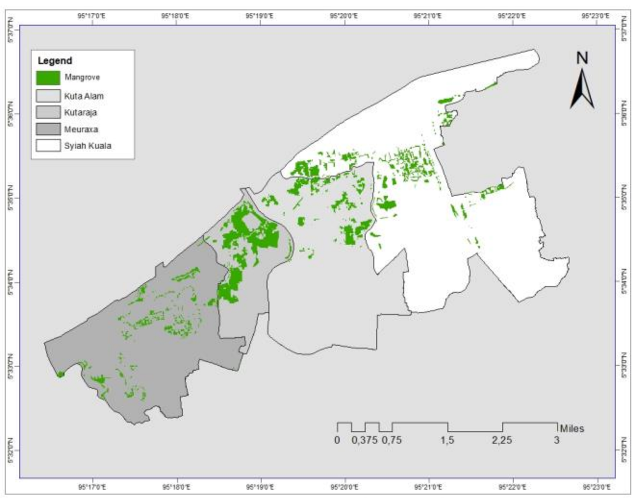

Figure 4. Mangrove areas of Banda Aceh City, Aceh Province, Indonesia

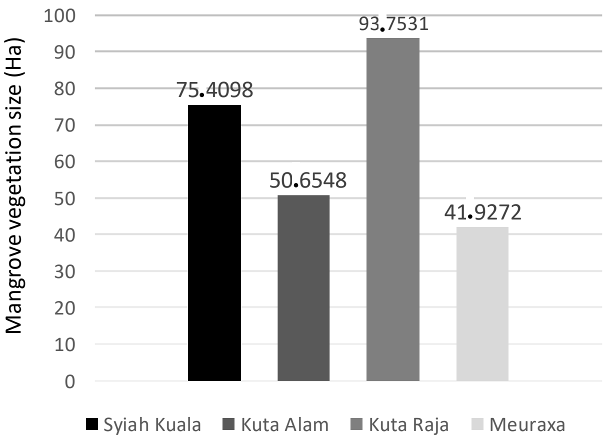

Figure 5. Extent of mangrove vegetation in Banda Aceh City, Aceh Province, Indonesia

The mangrove area in Banda Aceh City in Figure 3 was automatically calculated using geometry in ArcGIS. The total mangrove area in Banda Aceh was found to be 261.74 hectares, a significant increase compared to the previous study. For example, Affan et al. (2019) reported that the mangrove area in Banda Aceh City was only 18.08 hectares in 2005, following the Tsunami. By 2013, the area had expanded to 66.30 hectares, and by 2015 it was 68.18 hectares. In 2018, the mangrove area had further increased to 76.15 hectares. The continued growth in mangrove vegetation in Banda Aceh City is the result of collective efforts by the government, non-governmental organizations, academics, and private companies aimed at environmental conservation and mangrove planting. According to data from the BPS Aceh (2015), the total area of Banda Aceh City was 5,090.98 hectares, meaning that mangroves covered only 0.05% of the total area. Among the four sub-districts analyzed, Kuta Raja had the largest mangrove area, covering 93.75 hectares. This area has expanded since 2004, when the mangrove area was only 66.25 hectares. After the Tsunami, this area decreased to 47.9 hectares in 2015 (Saputra et al. 2016). Syiah Kuala, Kuta Alam, and Meuraxa (Figure 5) also experienced an increase in mangrove area compared to previous years.

The increase in the area of mangrove vegetation in Banda Aceh City occurred due to initiatives taken by various parties, both government, non-government, academics, and private companies to protect the environment by planting mangroves. This initiative aligns with the findings of Anhar et al. (2024), who reported that PT Pertamina Patra Niaga Fuel Terminal Krueng Raya planted 1,000 mangrove seedlings in the Lampulo Mangrove Park Area, Kuta Alam District, with the objective of environmental conservation.

Mangrove areas are dynamic and constantly changing due to various human factors. While human activities often lead to a reduction in mangrove areas, efforts such as planting activities carried out by different parties contributed to the expansion of mangrove areas. Human activities that lead to the conversion of mangrove lands for purposes such as aquaculture, settlement development, and tourism often result in the loss of mangrove areas. Specifically, changes in mangrove land use for aquaculture have been shown to increase carbon loss and accelerate mangrove depletion significantly (Aunurrahman et al. 2023; Wongprom et al. 2023). The research also shows several human activities that threaten mangrove areas, such as cutting mangroves for wood, converting land for housing, and transforming mangrove areas into fish ponds for economic purposes. Although the mangrove areas in Banda Aceh City have increased yearly, converting large-scale areas into residential zones and fish ponds threatens the sustainability of mangrove areas. If this trend continues, it is feared that mangrove areas will decrease rather than increase in the coming years. Therefore, it is essential that both the local government and surrounding communities pay greater attention to the proper management and conservation of mangrove areas.

Mangrove carbon stocks

Protecting these areas is vital not only for safeguarding the coastal ecosystem from erosion and sea wave impacts, such as Tsunami waves, but also for using mangroves to mitigate global warming. According to Fatonah et al. (2023), mangrove forests significantly mitigate climate change by helping reduce CO_2 concentrations in the atmosphere. One of the main drivers of global warming is the increase in greenhouse gas emissions caused by human activities. Researchers and governments have proposed direct carbon sequestration by trees, including mangroves, as an urgent measure to stop and reduce carbon dioxide (CO_2) increase in the atmosphere. Mangrove vegetation can help combat this problem by absorbing CO_2. Pricillia et al. (2021) and Purwanto et al. (2021) emphasized the important role of mangrove ecosystems in providing ecosystem services, such as carbon-absorbing and storage, thus contributing to global warming mitigation. Calculating mangrove carbon stocks is essential for assessing their contribution to mitigating climate change. This data is also crucial for developing strategies to protect mangrove areas and supporting environmental policies, such as mangrove carbon trading.

Spatial modeling of carbon stock values processed using ArcGIS presents the results in maps grouped into three density classes: high, medium, and low. The analysis reveals that in the Syiah Kuala Sub-district, the total carbon stock at low, medium, and high-density ranges from 0 to 28.43 t C ha^{-1} (Figure 6). In the Kuta Alam Sub-district, the total carbon stock ranges from 0 to 40.78 t C ha^{-1} (Figure 7). In the Kuta Raja Sub-district, the total carbon stock ranges from 0 to 38.97 t C ha^{-1} (Figure 8). In the Meuraxa Sub-district, the total carbon stock at low, medium, and high-density ranges from 0 to 34.00 t C ha^{-1} (Figure 9). The differences in carbon stocks among sub-districts are not substantial, as the mangrove density across all sub-districts is relatively identical. This study's mangrove carbon stock values are higher than those found in research by Fatonah et al. (2023), who reported carbon values ranging from 12 to 37 t C ha^{-1} in rehabilitated mangrove areas.

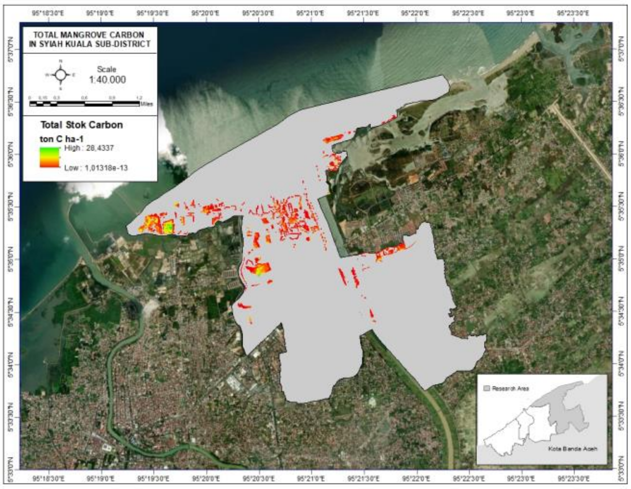

Figure 6. Total mangrove carbon in Syiah Kuala Sub-district, Banda Aceh City, Aceh Province, Indonesia

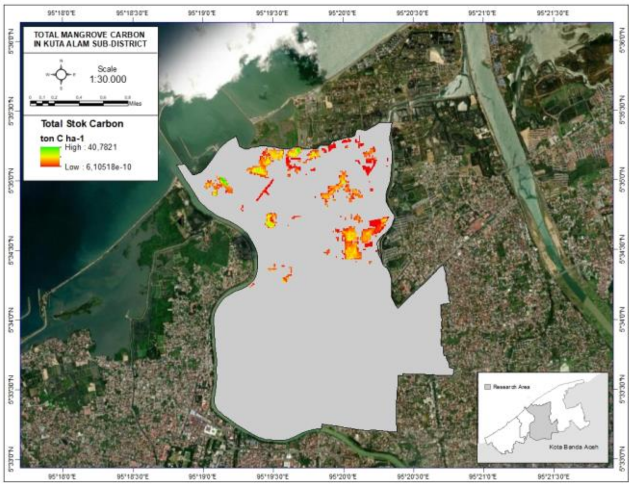

Figure 7. Total mangrove carbon in Kuta Alam Sub-district, Banda Aceh City, Aceh Province, Indonesia

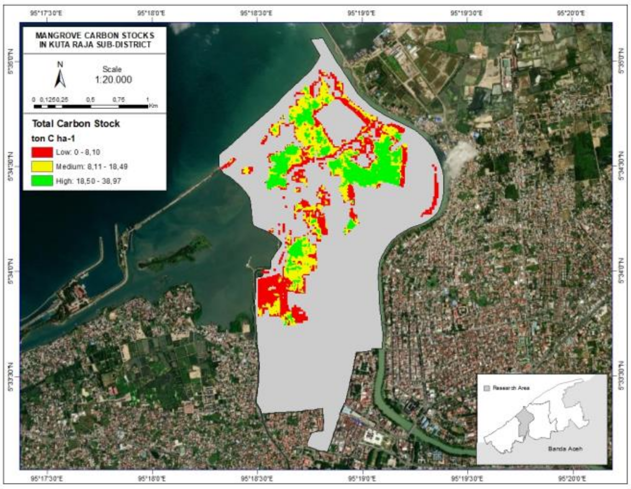

Figure 8. Total mangrove carbon in Kuta Raja Sub-district, Banda Aceh City, Aceh Province, Indonesia

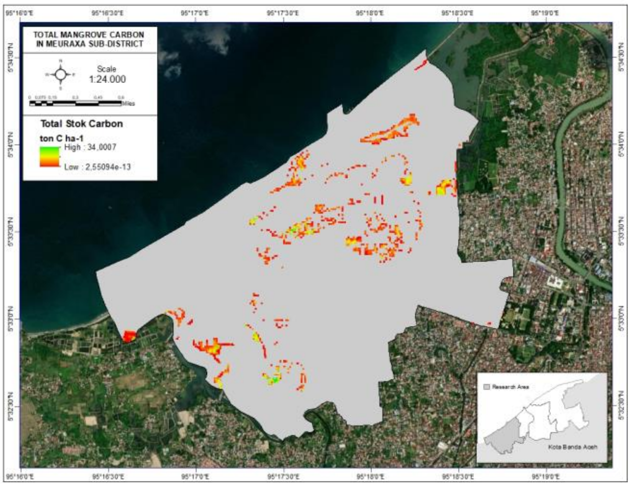

Figure 9. Total mangrove carbon in Meuraxa Sub-district, Banda Aceh City, Aceh Province, Indonesia

Carbon stock values vary across sub-districts in Banda Aceh City due to differences in mangrove density. This finding aligns with the research conducted by Hambali et al. (2023) in Labuan Tereng, Lombok Barat, where the lowest carbon stock estimate was 0.02-10.46 t C ha^{-1} in the very sparse density class, while the highest carbon stock value obtained was approximately 58.30-59.02 t C ha^{-1} in the very high-density class. This indicates that the carbon stock value is proportional to the vegetation density class. According to Hilmi et al. (2024), carbon storage is influenced by tree density and the percentage of carbon in the ecosystem. Zulhalifah et al. (2021) further suggested that higher mangrove leads to greater carbon content, with factors such as stand density, composition, structure, and the quality of mangrove habitat all affecting biomass accumulation and carbon storage.

In conclusion, within the study area, the Kuta Raja Sub-district has the largest mangrove area, with 93.75 hectares, followed by Syiah Kuala with 75.40 hectares, Kuta Alam with 50.65 hectares, and Meuraxa with 41.92 hectares. The highest mangrove carbon stock value is found in the Kuta Alam Sub-district, with values ranging from 15.99 to 40.78 t C ha^{-1}. These results highlight the need for developing rehabilitation strategies and sustainable management of mangrove areas to ensure the longevity of coastal ecosystems and support efforts to mitigate global warming through the ecosystem services provided by mangroves.

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