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MANGROVE DENSITY AND REMOTE SENSING-BASED ABOVE-GROUND CARBON STOCK ESTIMATION IN SEGARA ANAKAN, CILACAP, CENTRAL JAVA

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ABSTRACT

The Segara Anakan mangrove ecosystem in Cilacap, Central Java, is one of the largest mangrove areas on Java Island and plays vital ecological, economic, and climate-related roles. This study aimed to analyze the spatial distribution of mangrove vegetation density and estimate the potential Above-Ground Carbon (AGC) stock of the ecosystem using remote sensing technology. Sentinel-2A satellite imagery was processed using the Normalized Difference Vegetation Index (NDVI) to classify mangrove density while Above-Ground Biomass (AGB) data obtained from the Global Mangrove Watch database were converted into AGC using an IPCC carbon conversion factor of 0.47. The results showed that the total mangrove ecosystem covered 7,516 ha, with dense mangroves representing the dominant class, primarily distributed in the central and inner parts of the lagoon. This dense density class dominates over the moderate and sparse density classes, indicating that the mangrove vegetation structure in this area remains relatively good. The estimated mean AGC was 119.85 tons ha^{-1}, resulting in a projected total AGC of 900,792.6 tons. These findings indicate that the Segara Anakan mangrove ecosystem has a substantial capacity for carbon sequestration and storage at the regional scale. However, anthropogenic pressures, including land use conversion and high sedimentation dynamics, pose significant threats that should be addressed through sustainable conservation and spatially informed management strategies.

Keywords: Above-ground carbon stock, Sentinel-2A, mangrove density, Segara Anakan

INTRODUCTION

Mangrove ecosystems are one of the coastal ecosystems that carry very important ecological, economic, and social functions. Mangroves serve as a natural protector of coastlines against abrasion and seawater intrusion, as habitat for various aquatic biota, as spawning grounds, nursery grounds, and feeding grounds for numerous species of flora and fauna (Lepar et al., 2025). In addition, mangroves provide economic benefits for coastal communities through the fisheries and tourism sectors as well as the utilization of non-timber forest products (Nasution et al., 2025). Indonesia possesses extensive mangrove forests with a high level of biodiversity, making the presence of mangroves an important component in maintaining the balance of coastal ecosystems (Suryadi et al., 2021). Mangrove ecosystems have the capacity to absorb and store large amounts of carbon, a function known as blue carbon. This capacity gives mangroves an important role in mitigating global climate change caused by rising greenhouse gas emissions (Azizah et al., 2024).

One important mangrove area in Indonesia is Segara Anakan. This area is a coastal lagoon located in Cilacap Regency, Central Java. The mangrove ecosystem in Segara Anakan plays a significant role in supporting water productivity, maintaining coastal stability, and serving as a source of livelihood for the surrounding community. In addition, this area holds considerable potential as a coastal carbon sink due to the high biomass of mangrove vegetation found there (Semito et al., 2025). Despite its highly important ecological functions, the condition of the mangroves in Segara Anakan has been subjected to various environmental pressures and anthropogenic activities. High sedimentation originating from the Citanduy River watershed has caused changes in the lagoon's morphology and has affected the dynamics of the mangrove ecosystem. Furthermore, logging activities, land-use conversion into aquaculture ponds and settlements, and increasing human activity in coastal areas have also contributed to mangrove degradation. Previous research has reported that the Segara Anakan area has experienced very high sedimentation, which has altered tidal patterns and affected the distribution of mangrove vegetation. This degradation has also had an impact on the decline in habitat quality and fisheries resource productivity in the coastal area (Semito et al., 2025).

Changes in mangrove condition can be identified through analysis of mangrove vegetation density. Mangrove density is one of the key indicators used to determine the health status and condition of a mangrove ecosystem. Generally, the higher the vegetation density, the better the ecological condition of the area. Analysis of mangrove density can currently be carried out effectively using remote sensing technology and Geographic Information Systems (GIS). The use of satellite imagery such as Landsat and Sentinel-2A enables the monitoring of mangrove conditions both spatially and temporally, covering wide areas within a relatively efficient timeframe. Compared to Landsat and other satellite imagery, Sentinel-2A was selected for this study because it offers a higher spatial resolution (10 meters), a better temporal resolution with a shorter revisit time, and free access, enabling it to detect changes in mangrove vegetation conditions in a more detailed and accurate manner. Vegetation indices such as the Normalized Difference Vegetation Index (NDVI) are also widely used to identify the level of density and health of mangroves (Amal et al., 2023).

In addition to density analysis, the estimation of mangrove carbon stock is an important aspect of sustainable coastal ecosystem management. Carbon stock estimation is needed to determine the capacity of mangrove ecosystems to sequester carbon and to support climate change mitigation efforts. The magnitude of carbon stock is generally influenced by vegetation condition, biomass, mangrove species, and canopy density. Therefore, analyzing the relationship between mangrove density and carbon stock estimation is important in order to provide comprehensive information regarding the ecological condition of mangrove areas (Semito et al., 2025).

Various studies on mangroves in Segara Anakan have been conducted; however, most of these studies have focused on changes in mangrove area extent, vegetation health, or mangrove community characteristics. Research integrating mangrove density analysis with remote sensing-based carbon stock estimation remains relatively limited, particularly studies that comprehensively describe the spatial distribution of carbon stock. Yet, such information is highly important as a basis for coastal area management, mangrove rehabilitation, and the formulation of coastal ecosystem-based climate change mitigation policies. Therefore, research on mangrove density analysis and above-ground carbon stock estimation in Segara Anakan needs to be conducted in order to obtain information on the spatial condition and potential of the mangrove ecosystem. The results of this research are expected to serve as a source of scientific information to support conservation, rehabilitation, and sustainable management efforts of mangrove ecosystems, as well as to support climate change mitigation programs in coastal areas.

MATERIALS AND METHODS

Time and Location of Research

The research was located in the Segara Anakan Mangrove Ecosystem area, Cilacap Regency, Central Java Province, Indonesia, at coordinates 7°37'22"–7°47'37" S and 108°45'11"–109°2'54" E. This study used ArcGIS 10.8, Microsoft Excel 2019, and Microsoft Word 2019. The data used were Sentinel-2A data acquired on April 25, 2026, obtained from https://dataspace.copernicus.eu/; mangrove distribution and carbon stock data obtained from https://www.globalmangrovewatch.org/; hillshade data obtained from https://www.lapakgis.com/; and Indonesian shapefile data obtained from https://tanahair.indonesia.go.id/.

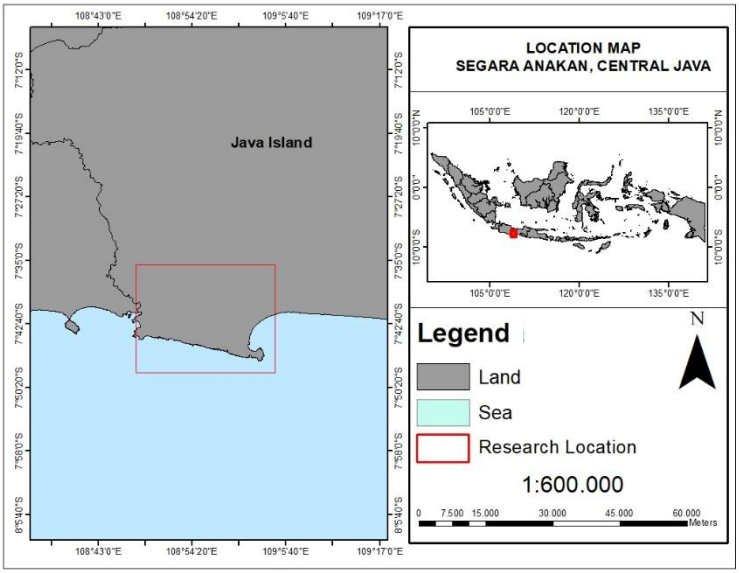


Figure 1. Map of the study Location.

Sentinel-2 Level 2A Image Data Acquisition

The primary data used in this study were multi-temporal Sentinel-2 Level 2A (Bottom of Atmosphere/BOA) satellite images downloaded through the Copernicus Browser platform or Google Earth Engine (GEE). Level 2A products were selected because they have already undergone automatic radiometric and atmospheric correction processing using the Sen2Cor processor developed by ESA, such that the resulting digital values represent surface reflectance (Main-Knorn et al., 2017). Image selection was based on a cloud cover level of less than 10% in order to minimize atmospheric interference on mangrove objects.

Image Pre-Processing

The image pre-processing stage consisted of clipping the study area and cloud masking. Image Clipping: Performed using vector data of administrative boundaries or the boundaries of the study area in Shapefile (SHP) format. Cloud Masking: Although cloud cover was below 10%, remaining cloud pixels and their shadows were eliminated using a classification algorithm based on the Scene Classification Layer (SCL) embedded in the Sentinel-2 Level 2A product (Louis et al., 2016). Spatial Resampling: Bands with a spatial resolution of 20 meters (such as Red-Edge Bands 5, 6, and 7) were resampled to a resolution of 10 meters to match the spatial resolution of the Red and NIR bands, using the Nearest Neighbor method to ensure consistency during index extraction (Frampton et al., 2013).

Analysis of Change and Density Level of Mangrove Vegetation

Multi-temporal detection of changes in mangrove extent was carried out through vegetation value extraction and supervised classification. Land cover classification was performed using the Random Forest (RF) or Support Vector Machine (SVM) algorithm. Training areas were classified into several categories: dense mangrove, moderate mangrove, sparse mangrove, and non-mangrove (Giri et al., 2011). Change detection maps between years were analyzed using the Post-Classification Comparison method to determine the extent of mangrove area experiencing deforestation (loss), revegetation (gain), or remaining unchanged (Congalton & Green, 2019). The NDVI was used to isolate mangrove objects from non-mangrove objects (such as water and bare land) while also identifying canopy density levels. The NDVI formulation was calculated using the equation (Rouse et al., 1974).

The assessment of mangrove vegetation density level was carried out using the NDVI, a vegetation index that has been widely validated in various coastal ecosystem studies (Amal et al., 2023). NDVI is an index derived from the ratio and subtraction operations of the spectral values of two image bands, namely the red (Red) band and the near-infrared (NIR) band. Although classified as a simple index in terms of its calculation, NDVI has a dynamic value range and a high level of sensitivity to changes in vegetation cover conditions, making it highly effective for detecting and mapping vegetation density and health spatially (Fadhillah et al., 2018).

The use of the Red and NIR bands in the NDVI calculation is based on the principle that these two bands exhibit contrasting spectral responses to the presence of chlorophyll and vegetation biomass. Healthy, dense vegetation absorbs energy in the red band for the photosynthesis process and reflects a high amount of energy in the NIR band, resulting in a higher NDVI value. Conversely, sparse vegetation or non-vegetated conditions produce low or even negative NDVI values. Operationally, NDVI is formulated as follows:

$$NDVI = (NIR - Red) / (NIR + Red)$$

Description:
NDVI : Normalized Difference Vegetation Index
NIR : Near-infrared radiation band of the pixel.
Red : Red light radiation band of the pixel.

The NDVI value has a theoretical range of −1 to +1. Values approaching +1 indicate very dense and healthy vegetation cover, while values approaching 0 indicate very sparse vegetation cover or non-vegetated surfaces such as bare land and water bodies. Negative values generally indicate water surfaces or other non-vegetated objects. The classification of mangrove density levels based on NDVI threshold values refers to the criteria developed by Amal *et al*. (2023) (Table 1).

Table 1. Mangrove density level based on NDVI

Mangrove Density Category	**NDVI Value**
Sparse Mangrove	-1 ≤ NDVI ≤ 0,32
Moderate Mangrove	0,33 ≤ NDVI ≤ 0,42
Dense Mangrove	0,43 ≤ NDVI ≤ 1,00

Source: Amal et al., 2023

Spatial distribution data on mangrove extent used as the baseline (shapefile) were obtained from the Global Mangrove Watch platform (https://www.globalmangrovewatch.org/). This shapefile data was integrated into ArcGIS software for further spatial analysis and processing. The next stage involved overlaying and clipping the baseline mangrove data (Global Mangrove Watch) with the mangrove density classification data to obtain the boundaries of the mangrove area that had been analyzed using NDVI.

Estimation of Above-Ground Carbon Stock Potential

The potential blue carbon stock was estimated based on mangrove AGB density values already available in the spatial reference data. The approach used in this study refers to the method developed by the IPCC (2006) as cited in Bachmid et al., (2018), which states that the organic carbon concentration contained in mangrove vegetation biomass amounts to 47% of the total biomass value. Accordingly, the AGC value within a given unit area of mangrove can be calculated by multiplying the biomass value by a conversion factor of 0.47. The equation used is as follows:

$$C : B \times 0,47$$

Description:
C : Amount of carbon stock (tons)
B : Biomass

The conversion factor of 0.47 is based on the assumption that carbon constitutes approximately 47% of the total dry organic matter of plant biomass, a value that has been widely recognized in the scientific literature on mangrove ecosystems (Bachmid et al., 2018). The mangrove distribution and carbon stock data were then overlaid with the mangrove density results, producing a map of mangrove distribution and density.

RESULTS AND DISCUSSION

Spatial Analysis of Mangrove Vegetation Density in Segara Anakan

Spatial analysis of mangrove density in the Segara Anakan area, Cilacap, Central Java, showed that the total extent of the mangrove ecosystem reached 7,516 hectares (Figure 2). The mangrove density classification results indicated the presence of three main cover classes, namely high-density (dense) mangrove, moderate-density mangrove, and low-density (sparse) mangrove. The spatial distribution of these three classes revealed that dense mangrove was the most dominant class and was widely distributed across the central and inland portions of the lagoon within the study area. The dominance of dense mangrove reflects an ecosystem condition that still retains a relatively solid vegetation structure, despite being under pressure from massive sedimentation dynamics. This condition is consistent with the characteristics of Segara Anakan as one of the largest mangrove ecosystem strongholds on the island of Java, which exhibits a high level of resilience to environmental change (Danardono et al., 2025). The spatio-temporal characteristics of this area demonstrate a consistent capacity for natural self-recovery through the growth of new mangrove colonies in areas of sediment accretion, which has continued to maintain its ecological function amid fluctuations in both anthropogenic and natural disturbances (Danardono et al., 2025; Semito et al., 2025).

The presence of high-density mangrove plays a very important role in maintaining the environmental stability of the coastal lagoon. Ecologically, mangroves function as a natural protector of land against the threat of abrasion, as a sediment trap for flows from large rivers such as the Citanduy River, and at the same time play a role in stabilizing the coastline through their complex root systems. The capacity of the mangrove root system to minimize the adverse impacts of the high suspended solid load and sedimentation rate of the Citanduy River is crucial in slowing the rate of shrinkage of the Segara Anakan lagoon's extent (Hilmi et al., 2021).

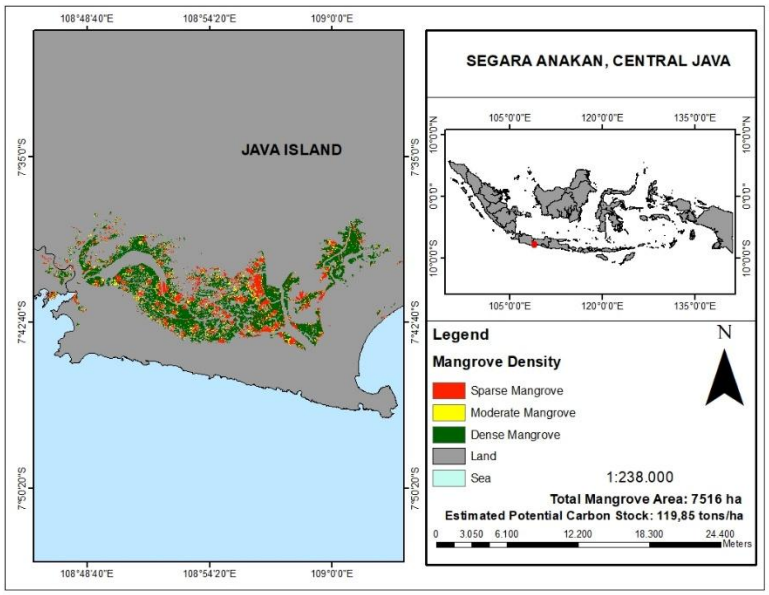


Figure 2. Mangrove Density and Carbon Stock Potential Estimation

These ecological functions make the Segara Anakan mangroves one of the key ecosystems in maintaining the sustainability of fisheries resources in the southern coastal region of Java (Suryono, 2015). From a socio-economic standpoint, mangroves also provide direct benefits to the communities in Kampung Laut District, such as supporting traditional fishing activities and providing non-timber forest products. The economic activities of the Kampung Laut community are highly dependent on the sustainability of this mangrove forest, particularly through the supply chain and economic value of mud crab and caught shrimp commodities, which serve as their primary source of livelihood (Junaidi et al., 2022).

Nevertheless, the spatial analysis results using Sentinel-2 imagery reveal the presence of clusters of moderate- and sparse-density mangrove categories distributed at certain points, particularly along the edges of sea transportation routes and areas directly bordering domestic activities. The presence of these density

classes indicates ongoing pressure on the mangrove ecosystem, arising from both natural factors and anthropogenic activities. The main factors influencing the decline in mangrove density in several sub-areas of Segara Anakan include land conversion into aquaculture ponds or agricultural land, settlements, and mechanical disturbance caused by community boat transportation activities. In line with the findings of Danardono et al., (2025) and the multitemporal analysis by Hilmi et al., (2022), the exploitation of Other Use Areas (APL) and buffer zones around Kampung Laut for aquaculture (pond) activities has continuously pushed natural mangrove stands further inland over space and time, triggering habitat fragmentation.

In addition to land-use conversion, excessively high sedimentation rates at certain extreme points can bury mangrove pneumatophores, causing habitat degradation that ultimately reduces the natural regeneration capacity of mangroves. This root-burial phenomenon is confirmed by research from Semito (2025) and is further reinforced by the findings of Hilmi *et al*. (2021), which demonstrated that uncontrolled sedimentation dynamics from the main river corridor not only degrade the lagoon's geometry but also directly reduce the vegetation canopy density index due to disrupted substrate stabilization and cellular respiration failure in the root systems of true mangroves in the intertidal zone of Segara Anakan.

Potential Estimation of Above-Ground Carbon Stock

The estimation results of mangrove carbon stock in the Segara Anakan area show an average value of 119.85 tons/ha. When accumulated over the total area of 7,516 ha, the Segara Anakan mangrove ecosystem is projected to be capable of storing a total organic carbon reserve of 900,792.6 tons. This significant value reflects the substantial carbon reserves stored within the ecosystem, both in the form of above-ground biomass, such as trunk, branch, and leaf components, and below-ground biomass, including root tissue and the accumulation of organic matter trapped in the lagoon's anaerobic sediment. Based on a study by Hilmi et al. (2019), the percentage and accumulation of carbon sequestration in the Segara Anakan lagoon area vary considerably among species and are influenced by the tree growth phase, with dominant constituent genera such as Rhizophora spp. and Bruguiera spp. playing a major role in the biomass storage structure of the stands. This high carbon stock value per hectare indicates that the mangrove ecosystem in Segara Anakan plays a highly crucial role as a carbon sink at both the regional and national scale.

Within the framework of environmental policy and the achievement of Indonesia's Nationally Determined Contribution (NDC) targets, the presence of the Segara Anakan mangroves, with a carbon storage capacity approaching one million tons, offers a strategic opportunity to support climate change mitigation programs through the blue carbon scheme. The high-density ecosystem in this area actively absorbs carbon dioxide from the atmosphere through an efficient photosynthesis process and isolates it for long periods within oxygen-poor sediment soil, thereby preventing the carbon from being released back into the atmosphere as a greenhouse gas. Research by Aulia et al., (2022) and the spatio-temporal analysis by Semito et al., (2025) demonstrated that the integration of remote sensing technology using Sentinel-2 satellite imagery is highly effective and accurate for mapping canopy density dynamics, which are directly proportional to the estimated fluctuations in carbon stock reserves in this intertidal area from year to year. Therefore, zonation-based protection, conservation, and rehabilitation efforts in Segara Anakan are not only important for maintaining the physical function of the coast against the threat of local environmental damage, but also represent a tangible, high-value contribution to the mitigation of the global climate crisis.

Species Composition and Vegetation Community Dynamics

Based on environmental baseline data and the literature on the Segara Anakan ecosystem, the mangrove vegetation composing this area is characterized by a diversity of tropical species representing zonation from the coast to the inland estuary. The family Rhizophoraceae is one of the main components dominating the area, represented by species such as Rhizophora apiculata and Bruguiera gymnorhiza. This family-level diversity indicates that the Segara Anakan area has a community structure that is highly adaptive to tidal fluctuations and the high freshwater input from the mainland of Java Island (Kresnasari & Gitarama, 2021). Species of the family Rhizophoraceae are known to possess a high capacity for morphological adaptation through their stilt root and knee root systems, which enable them to stand firmly on the thick muddy substrate resulting from high sedimentation as well as oxygen-poor/anoxic sediment conditions (Hilmi et al., 2015).

In addition, the presence of pioneer species such as Sonneratia alba (family Lythraceae) and Avicennia marina (family Acanthaceae) in the areas of newly emerged islands (accretion areas) plays a highly vital ecological role. These pioneer species function to stabilize the muddy sediment carried by river flows, accelerate the soil consolidation process, and gradually prepare the substrate environmental conditions to

become suitable for the succession of other mangrove species behind them (Hilmi et al., 2015; Kresnasari & Gitarama 2021). The dense pneumatophore root system of these pioneer species has proven highly efficient in trapping suspended particles in Segara Anakan, making them a natural agent in the dynamics of coastal land formation in the lagoon, which continues to experience intensive shallowing (Hakiki et al., 2021; Hilmi et al., 2022).

Overall, the species composition distributed throughout Segara Anakan illustrates an ecosystem currently caught in a dynamic ecological interplay between natural recovery and external pressure. This structural balance must be maintained to prevent excessive dominance by opportunistic species resulting from extreme changes in salinity or mud thickness (Hilmi et al., 2015). Given the anthropogenic pressures in the form of land conversion and area degradation at points of sparse density, periodic monitoring using the integration of Sentinel-2 remote sensing data and field validation of species composition becomes a highly important agenda (Hilmi et al., 2022). This step is necessary to detect changes in community structure and declines in stand quality as early as possible, before the damage reaches an ecological threshold that is difficult to restore.

In addition, the mangrove ecosystem in Segara Anakan also serves as an important habitat for various aquatic biota, functioning as a spawning ground, nursery ground, and feeding ground for economically valuable commodities such as shrimp, mud crab (Scylla serrata), and various species of estuarine fish. This ecological relationship is supported by the study of Ismail et al., (2019), which confirmed that fluctuations in mangrove density and vegetation degradation in the Segara Anakan area have a strong linear correlation with the rise and fall in the volume of mud crab (Scylla sp.) catches by local fishermen.

Study Limitations and Suggestions for Future Validation

Several factors should be considered when interpreting the results of this study. The mangrove density assessment was based on a single Sentinel-2A image, therefore represents mangrove conditions at a specific observation time rather than temporal variations in vegetation condition. In addition, the AGC was estimated from AGB data provided by the Global Mangrove Watch database using a carbon conversion factor of 0.47. These estimates were not directly validated using field measurements, which may limit the assessment of their site-specific accuracy.

Further validation through field measurements would strengthen the reliability of the results, particularly by incorporating mangrove structure, biomass, and carbon stock collected close to the satellite acquisition date. Field observations would provide independent reference data for evaluating the NDVI-based density classification and AGC estimates. The use of multi-temporal Sentinel-2 imagery could also provide a more comprehensive assessment of temporal variations in mangrove density and support more robust estimation of mangrove carbon stock.

CONCLUSION

Remote sensing-based analysis showed that the Segara Anakan mangrove ecosystem covers an area of 7,516 ha, dominated by the high-density class (dense mangrove) distributed across the central and inland parts of the lagoon. This dense density class is the most dominant category compared to the moderate and sparse density classes, indicating that the area still retains a good vegetation structure. Meanwhile, moderate and sparse vegetation density was found mainly along the edges of sea transportation channels and areas directly adjacent to domestic activities. This vegetation density condition is reflected in the carbon storage capacity of the Segara Anakan mangrove ecosystem. The estimated above-ground carbon stock (AGC) showed an average value of 119.85 tons/ha, with a total AGC potential reaching 900,792.6 tons, confirming the important role of the Segara Anakan mangroves as a regional-scale carbon sink and store, while also supporting the ecological functions of the coastal area. In particular, management and rehabilitation efforts should be prioritized in areas with moderate and sparse density classes to improve vegetation structure quality and carbon storage capacity in these areas. Furthermore, future studies should incorporate field validation to ensure the accuracy of remote sensing-based mangrove density classification results.

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