

Original article

Decadal Changes in Mangrove Canopy Cover and Carbon Stock in Jati Papak, Alas Purwo National Park, Integrating Satellite and Ground-Check Approaches

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Abstract

Mangrove ecosystems play a critical role in carbon sequestration. However, long-term changes in canopy cover and biomass remain poorly quantified in several regions. This study aims to analyze changes in canopy cover and carbon stocks of mangrove ecosystems using satellite imagery and compares these findings with direct measurements. The research focuses on Pangpang Bay, Jati Papak, in Alas Purwo National Park (TNAP), utilizing Landsat-8 (2014) and Sentinel-2 Level 2A (2024) imagery. Methods include collecting satellite image data, pre-processing data with a maximum cloud cover limit of 10%, analyzing canopy changes using the NDVI index and Random Forest algorithm, and carbon stocks estimation using InVEST software. Ground-check data were collected from five stations using the transect method to verify satellite-derived estimates and assess above-ground biomass and carbon stocks. Results revealed that there were three phases of vegetation growth in Jati Papak: seedlings, saplings with varying dominant species across phases. Seedlings and trees were dominated by *Rhizophora* spp., while saplings were primarily *Ceriops tagal*. The ecosystem had a low diversity level (Margalef Diversity Index 0 - 1.67). Satellite-delivered images showed an increase in canopy cover from 89.9 ha (2014) to 91.9 ha (2024), and in carbon stocks from 225.92 tons C/ha (2014) to 260.20 tons C/ha (2024). Ground-check measurement of above-ground carbon stock yielded 77.65 tons C/ha, predominantly contributed by *Rhizophora* spp. This study highlights the potential of integrating satellite-based and ground-based methods to monitor mangrove ecosystems in order to evaluate carbon stocks and ecosystem health.

Keywords: carbon stock, Jati Papak, mangrove, satellite-imagery

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Introduction

Indonesia boasts one of the world's largest mangrove forest areas, spanning extensive coastlines and river estuaries. Indonesian mangroves account for 26-29% of global mangrove forests (Hamilton & Casey, 2016), covering an area of 2.9 million hectares. A significant portion, approximately 1,200 hectares, is located within Alas Purwo National Park (TNAP) (Setiawan, 2023). Mangrove forests are essential for preserving the balance of coastal ecosystems, preventing shoreline erosion, and functioning as large carbon sinks (Ouyang & Lee, 2020). The mangrove ecosystem in TNAP is regarded as pristine because of its biotic and abiotic components, making it an optimal site for the study of carbon stocks where information remains limited.

Mangrove ecosystem is changing over time for various aspects; natural phenomena, residential development, conversion land to aquaculture (Sakti et al., 2020). These changes can result in carbon storage being released and reduced CO₂ absorption (Segaran et al., 2023). In addition, changes in mangrove ecosystems also affect coastal biodiversity and harm local communities due to the depletion of natural resources such as timber and fisheries (Rahmadi et al., 2023).

Monitoring of these changes and applying them to conservation actions requires accurate estimation of carbon stock. It can be carried out with two basic methodologies such as terrestrial measurements and remote sensing. While remote sensing uses methods such as the Normalized Difference Vegetation Index (NDVI), ground-based assessments use allometric equations based on tree diameter measurements. Although field measurements yield accurate data, they require a significant amount of time and resources. On the other hand, although field data is needed for confirmation, remote sensing allows for wide coverage and temporal efficiency (Larekeng et al., 2024; Suhaili et al., 2020). Geographic Information Systems (GIS) have become a vital tool in remote sensing, combining spatial data to illustrate changes in land use, evaluate vegetation indices, and calculate mangrove carbon stores. (Hidayah et al., 2022; Villacreses et al., 2022).

Despite the widespread use, ground checks and remote sensing are infrequently set, particularly in TNAP. This study analyzes long-term changes in TNAP's mangrove forests to determine remote sensing's carbon stock estimation accuracy. This study examined ecological alterations, including canopy cover and carbon sequestration by comparing data from 2014 and 2024. The transition from Landsat-8 to Sentinel-2 enhances monitoring accuracy and mangrove dynamics understanding. Satellite analysis combined with field observations will fill information gaps and aid conservation and management initiatives.

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Methods

Study Site

Observations on mangrove ecosystem changes were carried out in the Jati Papak Mangrove Ecosystem, located in Alas Purwo National Park (TNAP), East Java, Indonesia. The analysis of mangrove ecosystem changes

through satellite imagery was conducted at the Laboratory of Ecology and Tropical Ecosystem Restoration, Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Brawijaya, Malang. For ground-check, there were five stations in this conservation area (Figure 1).

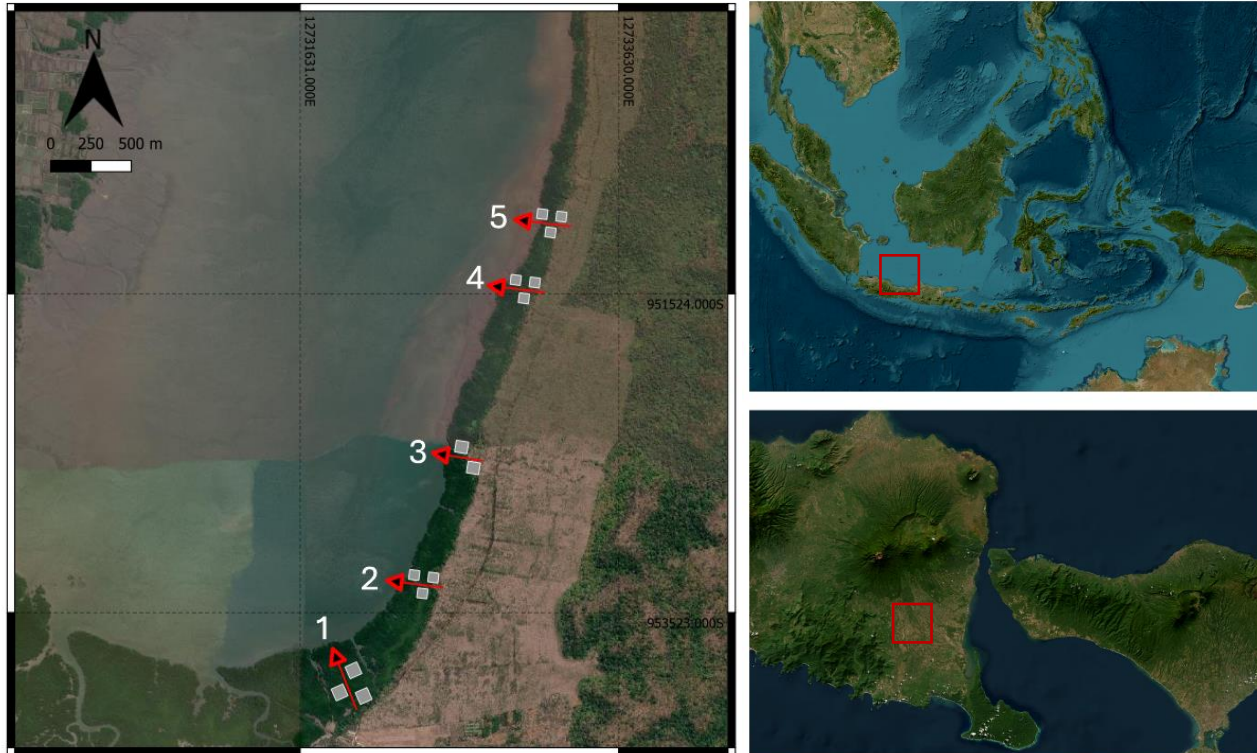


Figure 1. Distribution of sampling locations in the mangrove area of Jati Papak, TNAP is shown by the red arrow

Estimation of Canopy and Carbon Stock Change Using Satellite Imagery

The study utilized high-resolution Sentinel-2 Level 2A and Landsat 8 imagery for detailed mangrove mapping over a 10-year period (2014–2024). Sentinel-2 Level 2A provides ideal wavelengths for vegetation assessment (Phiri et al., 2020), and Very High Spatial Resolution (VHSR) enhances canopy mapping (Taureau et al., 2019). Satellite images were filtered using Google Earth Engine and ensured that cloud cover did not exceed 10% (Sudmanns et al., 2020). The analysis focused on the Jati Papak mangrove, TNAP, using false color composite (bands 564) to enhance canopy identification (Hariyanto et al., 2023). Canopy change was evaluated by NDVI, which classified the structure according to reflectance (Taureau et al., 2019). In this study, the Random Forest algorithm was used during the processing of NDVI-indexed images with machine learning to achieve accurate classification (Purwanto et al., 2022). Results were validated through ground-checking in TNAP, producing comparative canopy change maps.

Carbon stock estimation using Sentinel-2 Level 2A images, in which NDVI was applied to evaluate carbon reservoirs in the above-ground, below-ground, soil, and apoplastic (Huang et al., 2022). Biomass data for Above Ground (AGB) and Below Ground (BGB), as provided

by the Ministry of Environment and Forestry of Indonesia, were incorporated into the InVEST software to generate carbon stock values for the years 2014 and 2024.

Mangrove Vegetation Analysis and Carbon Stock Measurement

Ground-checking was carried out to identify the composition of mangrove vegetation in TNAP and to directly measure carbon stock. Observations were performed at five stations, each comprising three replicated transect plots. Transects were extended in the direction of the coastline using the nested sampling method (Hasidu et al., 2021). Vegetation parameters such as density (K), height (m), and diameter were measured. Mangrove biomass was assessed through measurements of Diameter at Breast Height (DBH) (S. Li et al., 2023) while the above-ground carbon stock was estimated using species-specific formulas developed for mangrove vegetation.

Data Analysis

Vegetation analysis data was compiled into graphs using Microsoft Excel. The correlation between canopy cover and carbon stock was analyzed using Pearson's test, based on NDVI data and carbon stock estimates derived from satellite imagery (2014 and 2024).

Results and Discussion

Mangrove Canopy Dynamics in TNAP: A Decade of Change

The classification of mangrove canopy cover in TNAP was based on variations in color and texture iden-

tified in satellite imagery. To analyze changes in canopy cover, Landsat-8 imagery from 2014 and Sentinel-2A imagery from 2024 were used (Figure 2). Sentinel-2A, with a higher spatial resolution of 10 meters per pixel, provides better visualization compared to Landsat-8 (Phiri et al., 2020).

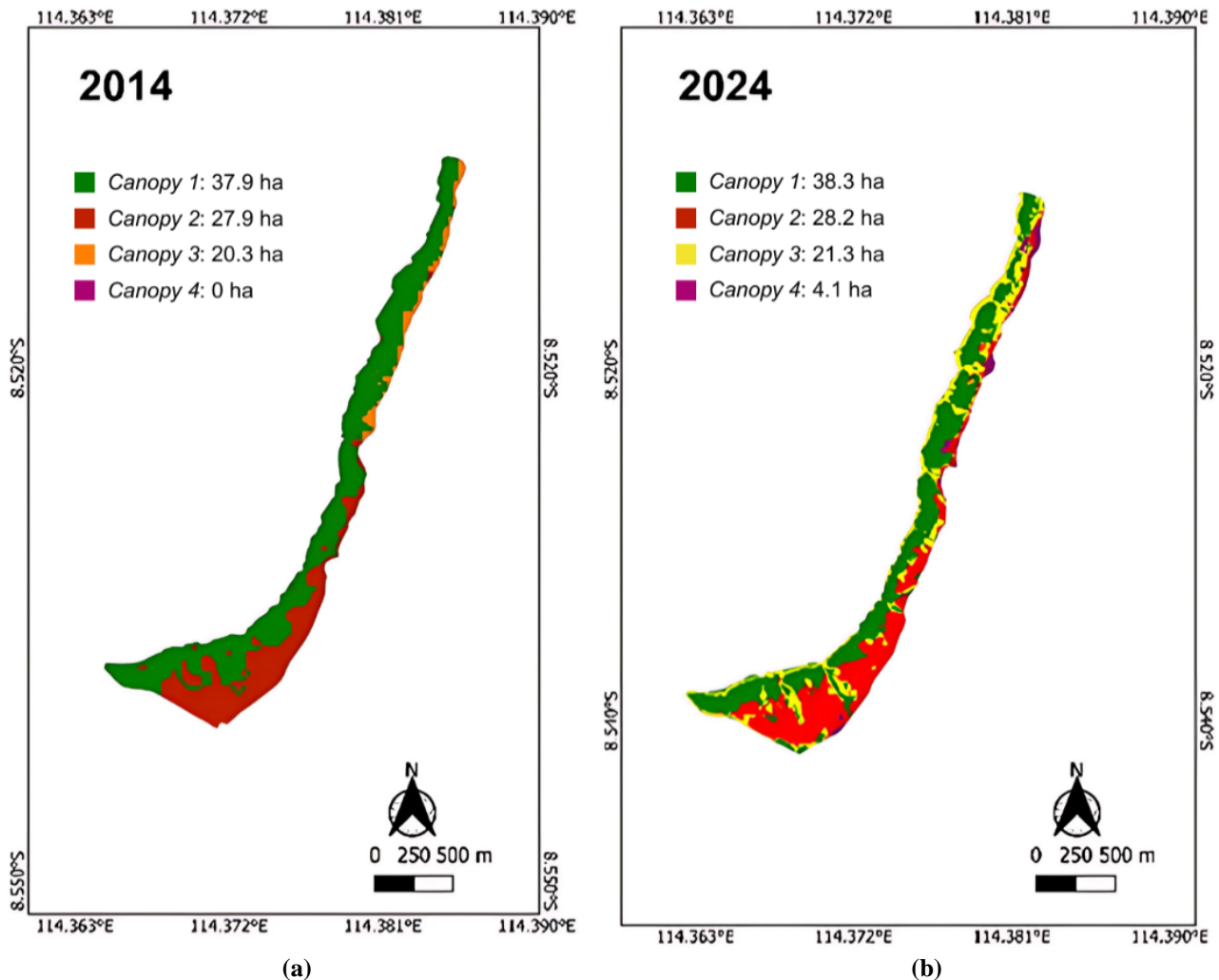


Figure 2. Visualization of random forest classification results of mangrove areas in Jati Papak for the years 2014 (a) and 2024 (b) shows changes in canopy cover and vegetation distribution

The Random Forest algorithm was utilized for canopy change detection, categorizing mangrove vegetation into four distinct canopy types as training inputs (Figure 2). The 2014 imagery analysis revealed three canopy classes (Figure 2a), whereas the 2024 imagery identified four classes (Figure 2b). The improved red-edge and near-infrared bands of Sentinel-2A, which assist in identifying different types of vegetation, are responsible for this boost in classification accuracy (Liu et al., 2018). Numerous studies indicate that texture variations in satellite imagery may indicate differences in vegetation and taxa. NDVI texture analysis facilitates species differentiation and assesses vegetation health by reflecting variations in canopy structure and leaf area index (Fang et al., 2023; Silveti & Bellis, 2024). Landsat-8 proves useful for classification; however, previous studies indicate its spatial limitations, which may be addressed through the

integration of additional satellite data (Soleimannejad et al., 2019). The 2024 classification indicates canopy expansion, especially within canopy classes three and four, implying mangrove growth over the past decade. Canopy cover is an important measure of mangrove health, influencing light penetration and promoting seedling development (Hanifa et al., 2024; Schaduw et al., 2024).

Canopy extent changes were quantified through pixel area calculations, resulting in hectares. The most notable rise occurred in canopy class three (yellow), which grew from 20.3 hectares in 2014 to 21.3 hectares in 2024. Canopy class two showed insignificant alterations, with an increase of only 0.3 ha, presumably due to competition among mangrove species (Nagarajan et al., 2008; Sam et al., 2023). Larger tree species typically demonstrate a broader canopy coverage compared to smaller species (Kuncayho et al., 2020). The canopy classifica-

tion results demonstrate positive growth trends in the Jati Papak mangrove ecosystem, highlighting successful conservation and natural regeneration over the last decade.

Mangrove Density and Regeneration Potential

Ten taxa were found in these five stations, including *Ceriops tagal*, *Rhizophora stylosa*, *Bruguiera cylindrica*, *Rhizophora mucronata*, *Sonneratia casiolaris*, *Avicennia marina*, *Sonneratia alba*, *Rhizophora apiculata*, *Avicennia alba*, and *Aegiceras corniculatum*. Based on Margalef diversity index (H'), the level of diversity among trees, saplings, and seedlings was at a low level ($H' = 0 - 1.67$) in all stations.

The high density of trees, saplings, and seedlings in the Jati Papak indicates the potential to support mangrove regeneration. Station 5, which had a high abundance of mangroves in all growth phases, was the station with the most ideal natural conditions to support mangrove regeneration (Figure 3) (Malik et al., 2019). Conversely, the lowest taxonomic richness of saplings was

found at Stations 1 and 3, which is assumed to be caused by environmental stress or the dominance of certain species (Latumahina et al., 2024). Seedling density was lowest at Stations 1 and 2, indicating diminished productivity, potentially affected by tidal cycles, pollution, and ecosystem age (Tharieq et al., 2023).

Our results were confirmed by ground-check observations, which showed variations in canopy cover and seedling establishment between locations. While Station 5 promoted spontaneous regeneration, the mangroves grown at Station 1 produced regular spacing and age, which may hinder the growth of seedlings and saplings. Under older trees with moderate canopy cover, where light penetration and organic matter accumulation were ideal, the density of seedlings and saplings was highest. Conversely, areas that were fully exposed or overly shaded showed poor seedling recruitment, highlighting the microhabitat (Dupuy & Chazdon, 2008; Mohan et al., 2024).

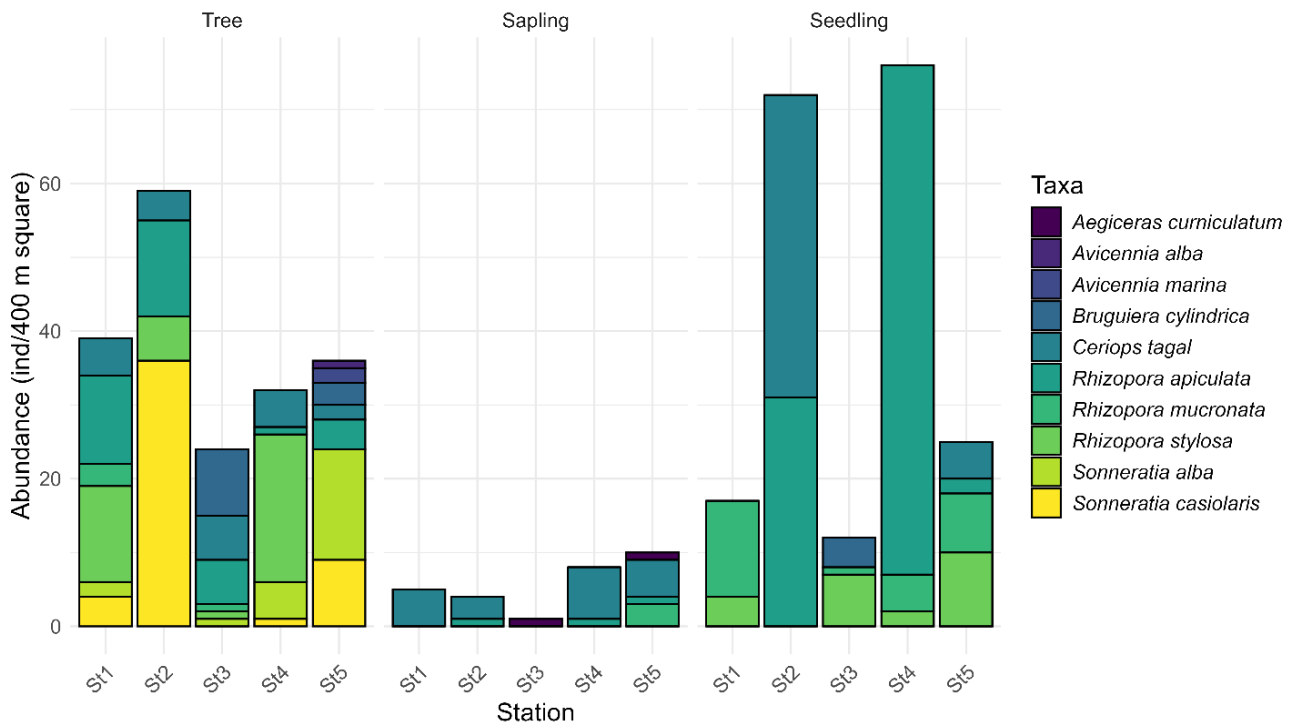


Figure 3. Mangrove structural composition: tree, sapling, and seedling density across sampling stations in Jati Papak (Note: St1 – St5 stands for Station 1 to Station 5, sequentially)

Mangrove regeneration potential in Jati Papak varies by taxon, influenced by propagule production, dispersal, seedling survival, and habitat preference. *Rhizophora* spp. (*R. stylosa*, *R. mucronata*, and *R. apiculata*) exhibited strong regeneration, dominating all growth stages with high survival rates, particularly in tidal-inundated areas (Figure 3). *R. stylosa* formed dense stands, stabilizing high-energy zones but restricting seedling diversity (Ismail et al., 2021; Wahyuningsih et al., 2024), while *R. mucronata* and *R. apiculata* thrived in Stations 1 and 3. *C. tagal*, found at all stages, showed the highest seedling recruitment at Station 4, thriving in semi-stable intertidal substrates and benefitting from partial shading in mixed

stands (Mughofar et al., 2018). In contrast, *Avicennia* spp. (*A. marina* and *A. alba*) displayed poor seedling regeneration, likely due to high seed predation or unstable substrate, though *A. corniculatum* exhibited moderate establishment in mudflats (Rizki et al., 2015). *Sonneratia* spp. (*S. alba* and *S. casiolaris*) faced recruitment challenges, with competition possibility between *S. alba* and *Rhizophora* at Station 3, while *B. cylindrica* seedlings were restricted to sheltered, low-energy environments (Aluri & Karyamsetty, 2018; Djamaluddin, 2018). Limited seedling survival in dynamic tidal zones suggests habitat-driven constraints on regeneration, emphasizing the need for species-specific conservation efforts.

Understanding Mangrove Carbon Storage: Variability, Species Contribution, and NDVI Correlation

Carbon stock estimation provides insights into the condition of mangrove vegetation, measurable through direct assessment or satellite imagery. InVEST software analysis reveals an increase in carbon stock from 225.92 tons C/ha (2014) to 260.20 tons C/ha (2024). This increase was very likely caused by the expansion of the mangrove canopy, indicating a possible increase in the number and the growth of individual plants from various species with diverse carbon storage capacities (N. Li et al., 2015). Arsalan et al. (2020) estimated the carbon stock in the Kalibiru Forest, Kulon Progo to be 96.67 tons C/ha, while the high carbon stock in Jati Papak is attributed to effective management (Christian et al., 2020).

In this study, different satellite sources were used, Landsat for 2014 and Sentinel-2 for 2024, which may have contributed to the variation in estimated carbon stock. The Landsat with 30-meter resolution makes it difficult to capture fine-scale canopy structure, especially in patchy or narrow mangrove zones. On the other hand,

Sentinel-2 offers better resolution (10–20 meters) and additional vegetation-sensitive spectral bands, enabling more precise mapping of mangrove cover and condition. These improvements likely enhanced the accuracy of the 2024 carbon stock estimate. While the observed increase may reflect actual ecological recovery and canopy expansion, the influence of improved satellite data quality should also be taken into account when interpreting changes over time.

Ground check-based carbon stock estimation across five stations showed variations (Figure 4). Hutchison et al. (2014) classify carbon stock as very low (< 88.19 tons C/ha), low (88.19 – 308.65 tons C/ha), moderate (308.65 – 385.81 tons C/ha), or high (>385.81 tons C/ha) (Hutchison et al., 2014). The average carbon stock at Stations 1 and 4 was very low at 52.33 and 70.59 tons C/ha, respectively. Stations 2, 3, and 5 fell into the low category, with values of 114.28, 99.96, and 90.81 tons C/ha (Figure 4). Biomass, largely dependent on tree diameter, influences carbon stock, with larger diameters resulting in higher biomass accumulation (Manafe et al., 2016).

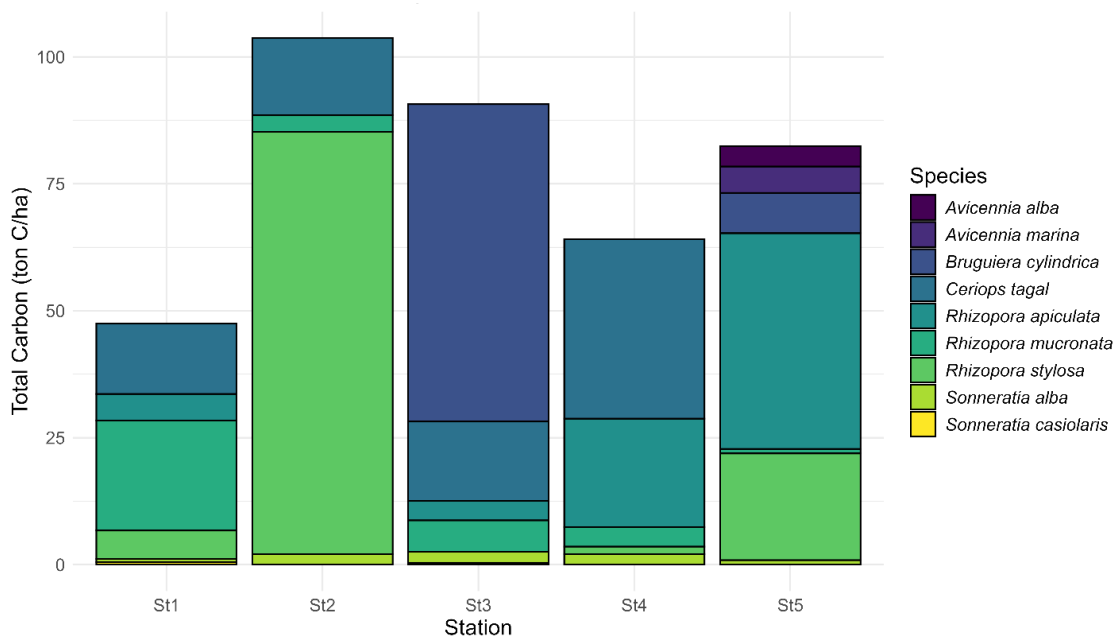


Figure 4. Species-specific above-ground carbon content across sampling stations (Note: St1 – St5 stands for Station 1 to Station 5, sequentially)

Mangrove carbon storage varies based on density, species diversity, and trunk size (Hairiah & Rahayu, 2007). Species-specific carbon stock contributions can be determined by their relative percentage (Figure 4). Station 2 has the highest carbon stock, and *R. stylosa* contributes about 80% of the total carbon stock, supported by its dominance. A study by Rahman et al. (2020) showed that *Rhizophora* significantly contributes to carbon stock in mangrove ecosystems. (Rahman et al., 2020). Of the five observed locations, *Rhizophora* was known to play an important role in three locations, and this genus was widely distributed in the Jati Papak area. Senoaji & Hidayat (2016) mentioned that mangrove species classified as hardwoods, such as *R. apiculata*, had a significant capacity/potential for carbon storage due to their large biomass (Senoaji et al., 2016).

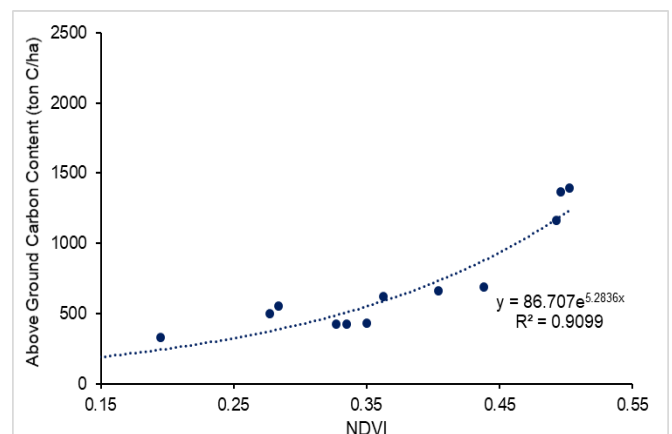


Figure 5. Exponential Relationship between NDVI and above-ground carbon content in Jati Papak mangrove forest

The relationship between NDVI and above-ground carbon content was analyzed using exponential regression and Spearman correlation. The results from the exponential model were more representative in explaining the relationship between NDVI and above-ground carbon content, and can be extended with other models, such as polynomial or Generalized Additive Models (GAM), for further validation. Therefore, the Spearman correlation test showed a value of $\rho = 0.0066$ (p -value = 0.9879), indicating no significant monotonic relationship between NDVI and above-ground carbon content. However, exponential regression produced $R^2 = 0.9099$, indicating that 90.99% of the variability of above-ground carbon content can be explained by NDVI (Figure 5). This difference occurs because Spearman correlation only measures monotonic relationships, while exponential regression captures more complex growth patterns. Some studies indicated that higher NDVI values correspond to increased carbon storage (Karmila et al., 2020; Kaskoyo et al., 2023).

Conclusion

Enhancing spatial resolution from Landsat-8 (2014) to Sentinel-2A (2024) improves the accuracy of canopy classification via the Random Forest algorithm. Results indicate canopy expansion, particularly in classes three and four, reflecting mangrove growth over the past decade. The analysis of mangrove structure indicates that Jati Papak exhibits significant regeneration potential, characterized by varying densities of seedlings and saplings across different stations. Estimates of carbon stock indicate an increase from 225.92 tons C/ha (2014) to 260.20 tons C/ha (2024) based on InVEST estimation, correlating with canopy expansion. The examination of the correlation between NDVI and above-ground carbon content (AGCC) indicated that the rise in NDVI is associated with enhanced above-ground carbon storage. The findings of this study indicate that the Jati Papak mangrove ecosystem exhibited positive growth, demonstrating the effectiveness of conservation and natural regeneration. However, variations in regeneration among stations necessitate focused attention in species-based conservation strategies.

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