JPPIPA 12(11) (2026)

Jurnal Penelitian Pendidikan IPA

http://jppipa.unram.ac.id/index.php/jppipa/index

Assessing Mangrove Cover Change and Aboveground Carbon Stocks in Banyuglugur Using Sentinel-2, InVEST, and Field Measurements

Tiara Fazilatunnisa[1], Muhammad Yusuf[1], Viky Vidayanti[1]*

[1] Department of Biology, Universitas Brawijaya, Malang, Indonesia

Received: December 16, 2025
Revised: August 22, 2026
Accepted: November 4, 2026
Published: November 30, 2026

Corresponding Author:
Viky Vidayanti
viky.vidayanti@ub.ac.id

DOI: 10.29303/jppipa.v12i11.13927

Open Access

© 2026 The Authors. This article is distributed under a (CC-BY License)

Abstract: Mangrove ecosystems play an important role in maintaining the balance of coastal environments. But in recent decades, the existence of mangroves has decreased. In the coastal area of Banyuglugur, Situbondo, mangrove rehabilitation has been carried out since 2018, but its effectiveness in changes in canopy cover and carbon stocks has not been widely studied. This study aims to analyze the changes in canopy cover and mangrove forest carbon stock in 2018 and 2025 in Banyuglugur based on satellite image analysis, to examine the relationship between canopy cover area and the amount of mangrove carbon stock, and to compare the estimation results of aboveground carbon stock derived from satellite imagery with ground measurements. The research used Google Earth Engine (GEE) and InVEST Carbon Storage and Sequestration Model software to estimate carbon storage within vegetation. Field validation was carried out through vegetation analysis using hemispherical photography. Results show a 4.12% increase in mangrove ecosystem area and a 35.83 Mg C ha^{-1} increase in aboveground carbon storage, based on InVEST estimates. Estimation using InVEST yields values 274% higher than direct measurements for the same carbon pools. The analysis of the relationship between canopy cover and aboveground carbon (AGC) stock showed no significant association. It can be concluded that the Banyuglugur mangrove ecosystem has experienced an increase in area and carbon stock. Correlation analysis between canopy cover and AGC shows a positive relationship ($\beta > 0$) but weak ($p > 0.05$). Carbon stock estimation using the InVEST model shows an overestimation compared to direct field measurements.

Keywords: Canopy cover; Carbon stock; Mangrove; Satellite imagery

Introduction

Mangrove ecosystems are among the coastal ecosystems with a significant capacity to sequester and store atmospheric carbon through biomass and sediment accumulation (Sholeh et al., 2024). This ability makes mangroves a major contributor to mitigating climate change (Aprilita et al., 2024). Indonesia is home to 20% of the world's mangroves (Suhardi et al., 2024), playing a crucial role in maintaining the global sustainability of blue carbon (Arfan et al., 2023).

Some mangrove areas in Indonesia are experiencing a reduction in mangrove area due to anthropogenic activities and natural events. It is estimated that 35% of the global mangrove area has been lost in the last 50 years (Wu et al., 2025). This degradation of the mangrove ecosystem leads to a decrease in vegetation and the ecological role of the mangrove ecosystem, and increases the vulnerability of coastal areas to coastal abrasion (Dewi et al., 2023). The Banyuglugur mangrove area in Situbondo Regency is one of the locations experiencing such pressure, along with the dynamics of coastal space utilization and local environmental changes.

In 2018, the Banyuglugur area 2018 became the location for a rehabilitation program coinciding with

How to Cite:
Putri, F. S., Harisuseno, D., & Sisinggih, D. Performance Evaluation of Historical CESM2 Rainfall Before and After Linear Scaling Bias Correction in the Sadar Watershed, Indonesia. *Jurnal Penelitian Pendidikan IPA*, *12*(11), 1–9. https://doi.org/10.29303/jppipa.v12i11.15770

National Santri Day. Following this intervention, an assessment of mangrove extent, canopy characteristics, and carbon stocks is needed to characterize the condition of the rehabilitated area. Periodic monitoring of these parameters is necessary to understand the extent of the recovery process, as carbon stocks are influenced by the type, size, and density of the vegetation stand. Research on natural and rehabilitated mangroves has demonstrated differences in aboveground biomass and stand structure (Sitthi et al., 2025), indicating that the area occupied by mangroves alone does not fully describe their condition. Banyuglugur therefore provides a case for examining whether changes in mapped mangrove extent and canopy indicators are consistent with the information obtained from carbon stock assessments.

Methods for monitoring mangrove ecosystems have developed significantly in recent years. Direct field measurements or observations (ground checks) have been supported by satellite image-based analysis. Analysis using satellite imagery enables the assessment of canopy cover changes and carbon stocks at the landscape scale, while field measurements provide reference data to evaluate the accuracy and potential bias of these estimates. Long-term monitoring using this method can provide important data on the spatial and temporal changes in mangrove cover (Sunkur et al., 2024). Another study used Landsat 8 and Sentinel-2A imagery, applying the NDVI algorithm and achieving accuracy rates of 75.51% for Landsat 8 and 87.50% for Sentinel-2A (Rafsenja et al., 2020). Additionally, software such as Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) enables the estimation of carbon stocks by assigning carbon densities to land-cover classes. However, when these densities remain fixed, modeled carbon changes reflect land-cover transitions rather than biomass growth within an unchanged class (Natural Capital Alliance, n.d.). Similarly, the accuracy of mangrove mapping does not by itself establish the ability of NDVI or canopy cover to represent aboveground carbon stocks. These methodological differences highlight the need to examine the agreement between model-based and field-based carbon estimates, together with the relationships between canopy indicators and field-based carbon stocks.

This study aims to (1) quantify changes in mangrove extent and NDVI between 2018 and 2025 using Sentinel-2 imagery, (2) compare InVEST-based aboveground carbon estimates with field-based estimates for 2025, and (3) examine the relationships of NDVI and field-measured canopy cover with aboveground carbon stocks. Its contribution is a site-specific assessment of the agreement and limitations of these complementary indicators for interpreting changes in a rehabilitated mangrove area.

Method

Location of the study

This research was conducted from August 2025 to December 2025. Field data collection was carried out in September 2025 in Banyuglugur, Situbondo, East Java. This ecosystem is located in a residential area and a small local fishing port. The data collected were then analyzed at the Tropical Ecology and Ecosystem Restoration Laboratory, Department of Biology, Faculty of Mathematics and Natural Sciences, Brawijaya University.

Collection and pre-processing of satellite image data

Canopy cover and carbon stock estimation data were obtained using Sentinel-2 satellite imagery from 2018 and 2025. The data acquisition and processing utilize the Google Earth Engine (GEE) platform, enabling efficient and consistent analysis on a large scale. During the pre-processing stage, Sentinel-2 images were selected based on visual quality with a maximum cloud cover limit of 10%. The pre-processing stage involved creating band composites by combining Sentinel-2 channels, which were then displayed as false-color composites (Purwanto & Asriningrum, 2019). Color composites are used to enhance the interpretation of canopy cover changes because they include visible and near-infrared spectral bands.

Analysis of canopy cover change

Land cover classification was performed using the Random Forest algorithm with three land cover classes: mangrove, non-mangrove, and water. Training data were obtained by digitizing areas on Sentinel-2 images and were used to train a model with 200 trees using six reflectance channels. The results of this classification produced a mangrove distribution map shown in pixels and area (ha). The accuracy of the classification was assessed using a confusion matrix, overall accuracy, and the Kappa statistic.

The NDVI value was calculated after the Random Forest classification to ensure that the vegetation index was applied only to pixels identified as mangroves. The NDVI calculation used the red (Red) and near-infrared (NIR) channels in the Sentinel-2 image. The NDVI results were then classified into three categories of mangrove canopy density: low (0.00–0.33), medium (0.34–0.42), and high (>0.43) (Simarmata et al., 2021).

Ground-truthing

Ground checks were conducted to verify the land-cover classification results and canopy-density

interpretations derived from Sentinel-2 imagery. Field observations were conducted by creating ten sample plots in the Banyuglugur mangrove area. Vegetation data collection in the mangrove ecosystem was classified into two categories (Rahmi et al., 2025): trees in 10 × 10 m plots (diameter ≥ 5 cm) and saplings in 5 × 5 m plots (diameter < 5 cm).

In each plot, the species of mangrove found was recorded, while the diameter (DBH) was measured as the basis for calculating aboveground biomass. Furthermore, canopy documentation was conducted using Hemispherical Photography at each plot, with three captures to estimate canopy cover. This method involves capturing images vertically toward the sky and the canopy cover (I. W. Dharmawan, 2020).

Above-Ground Carbon (AGC) Estimation

The carbon stock of the mangrove ecosystem is estimated using the InVEST Carbon Storage and Sequestration (CSS) Model software. Based on the classification results, an LULC table will be created with carbon pool values obtained from the Ministry of Environment and Forestry (KLHK). The CSS model calculates the amount of carbon stored per pixel based on land-use type and the corresponding carbon density. After that, the analysis results will be overlaid with the land-use layer in GIS. The values for each pixel are then summarized to create maps for different time periods (Zhu et al., 2024).

In addition to InVEST-based modeling, AGC was determined using field data from ground checks. Aboveground biomass was determined using allometric models according to mangrove type (Table 1). The carbon stock is subsequently computed from the biomass results using Formula 1.

$$Cb = B \times \%Corg \quad (1)$$

Cb : Carbon (kg)
B : Total biomass (kg)
%Corg : Percentage carbon content value (0.47)

The vegetation carbon stock data derived from field measurements provide an estimate and validation for interpreting the outcomes of the InVEST modeling.

Analysis of the Relationship between Canopy Cover, NDVI, and AGC

The relationship between mangrove canopy cover and carbon stock was analyzed using regression methods. The goodness of fit of a regression model can be assessed by the coefficient of determination (R^2). If the value of the coefficient of determination approaches 1, the resulting regression model is considered increasingly effective at describing the relationship between the two variables (Andiani et al., 2021). Additionally, correlation analysis was also conducted to measure the strength of the relationship between canopy cover and NDVI with carbon stock.

Table 1. Allometric biomass model for several species of mangrove vegetation

Species	Allometric Formula	Sources
Rhizophora mucronata	$B = 0.1466.DBH^{2.3136}$	(I. W. S. Dharmawan, 2010)
Sonneratia alba	$B = 0.825.DBH^{0.89}$	(Komiyama et al., 2005)
Avicennia marina	$B = 0.1848.DBH^{2.3524}$	(I. W. S. Dharmawan & Siregar, 2008)
Excoecaria agallocha	$B = 0.251.\rho .DBH^{2.46}$	(Komiyama et al., 2005)
Bruguiera cylindrica	$B = 0.251.\rho.DBH^{2.46}$	(Komiyama et al., 2005)

Note: B: biomass; ρ: wood density; DBH: diameter at breast height (1.3 m above ground level)

Result and Discussion

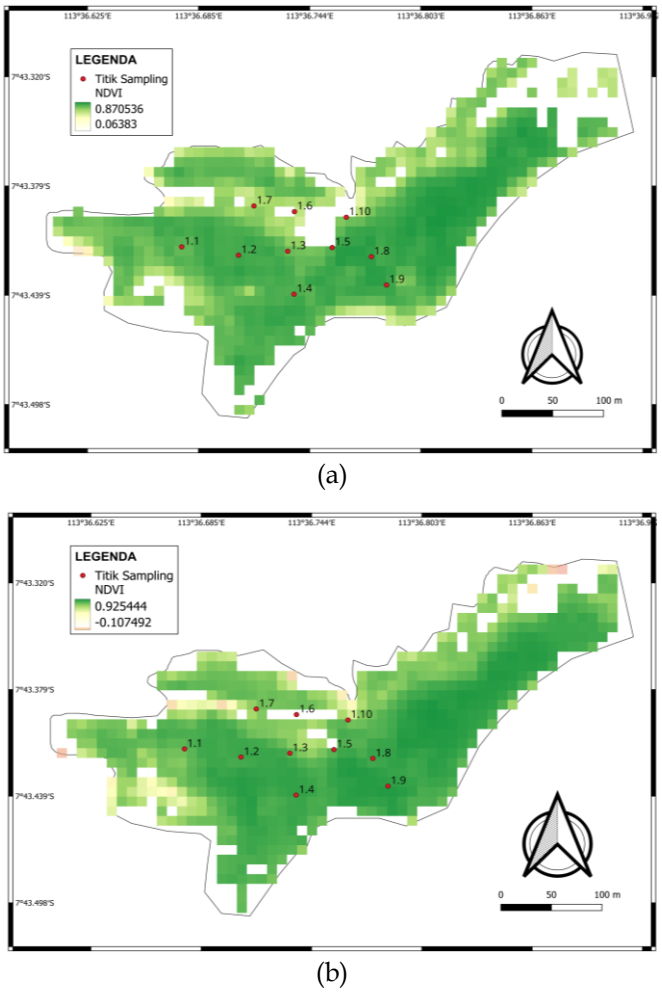
Changes in the mangrove canopy cover of Banyuglugur based on satellite imagery

The area of Banyuglugur mangrove, analyzed using a Sentinel-2 satellite image and classified with the random forest algorithm, shows an increase of 4.12% (Figure 2), with an accuracy of 99% and a Kappa coefficient of over 0.98. The mangrove area initially covered 6.55 ha in 2018 and increased to 6.82 ha in 2025, out of a total sampling area of 9.81 ha. This increase in area was clearly detected on the side adjacent to the sea and the northeast part.

In this study, the NDVI value was used to determine the health and density of mangrove vegetation. According to (Kusmana, Rahayu, & Ningrum, 2016), mangroves with low, moderate, and high densities have NDVI values of 0.26 – 0.3, 0.31 – 0.4, and > 0.41, respectively. Based on the average, the health of the Banyuglugur mangrove vegetation improved from 0.75 in 2018 to 0.81 (Figure 2). The mangrove vegetation in Banyuglugur increased at all density levels. The area with the highest density levels experienced the largest increase in area compared to the others, at 2.63% (Table 2).

The increase in the area of the Banyuglugur mangrove ecosystem, as determined by the random forest algorithm, indicates the successful regeneration of vegetation. This condition is common in mangroves that are in a stable state. Similar findings were also reported

that increased mangrove cover is closely related to successful rehabilitation and regeneration (Sasmito et al., 2020), and substrate stability (Sitthi et al., 2025). Furthermore, the application of the Random Forest algorithm in this work demonstrates remarkable dependability, evidenced by coefficient and Kappa values over 0.75 (Ma et al., 2022)



(a)

(b)

Figure 2. Spatial variation of NDVI for Banyuglugur mangroves in 2018 (a) and 2025 (b). Increased NDVI values are recorded through darker green gradations.

The observed area of this study also shows a rise, which is supported by the improved health of the vegetation, as reflected in higher NDVI values (Simarmata et al., 2021). Elevated NDVI values are frequently associated with increased biomass, canopy expansion, and improved productivity (Heumann, 2011). The presence of reduced minimum NDVI values in 2025 indicates a combination of mature and young vegetation. However, this index has limitations under very dense canopy conditions and is sensitive to water conditions.

Table 2. Variations in vegetation density as shown by NDVI

Density*	Mangrove area (ha)	
	2018	2025
Low	0.0052	0.0136
Moderate	0.0233	0.0269
High	6.5178	6.7763

*Low: 0.26 – 0.31, Moderate: 0.31 – 0.4, and High: > 0.41

Mangrove Aboveground Carbon Stock

The ground check revealed that the density of mangroves in the tree stand reached 1,660 individuals.ha^{-1}, while that of shrubs reached 520 individuals.ha^{-1}. The tree canopy comprised five taxa: *Excoecaria agallocha*, *Avicennia marina*, *Sonneratia alba*, *Bruguiera cylindrica*, and *Rhizophora mucronata*. The same taxa were identified in the shrub stands, except for A. marina and *S. alba* (Figure 3a). In the tree and shrub stands, it was found that *R. mucronata* had the highest density among to other species, with 850 and 320 individuals.ha^{-1}, respectively.

Based on direct observation data, the total AGC of tree and sapling stands in 2025 is 189.03 Mg C.ha^{-1}. Each identified vegetation individual is known to have a different carbon stock contribution, depending on its type and diameter size. In the tree stands, *R. mucronata* and *E. agallocha* are the primary contributors of AGC. In shrub stands, *E. agallocha* contributes the most compared to *R. mucronata* and *B. cylindrica* (Figure 3b).

Meanwhile, the results of estimating aboveground carbon stocks using InVEST suggest an increase in carbon stocks from 2018 to 2025 of 35.83 Mg C.ha^{-1} (Figure 3). The results of this aboveground carbon stock estimation are supported by the increase in the area of Banyuglugur mangroves based on classification results using the random forest algorithm. This condition is consistent with the study conducted by Gunawan et al. (2025), which found that an increase in the area of the mangrove ecosystem affects the amount of carbon stock stored within it. However, the carbon stock estimate using InVEST in 2025 is 274% higher than the results of direct carbon measurements.

The AGC in the Banyuglugur mangrove ecosystem indicates that variations in species and wood diameter are the main determining factors in biomass accumulation. Species, such as *R. mucronata* and E. agallocha, which have a larger diameter, contribute more carbon than other species. These findings are along with previous research, which show that the woods' structure, density, and diameter size, (Slik et al., 2013) and number of stands (Istomo et al., 2025) play a crucial role in determining the amount of mangrove biomass. Another study in Southeast Asia also reported that *R. mucronata* is the largest carbon sink in well-developed mangrove stands (Mulyana et al., 2021).Additionally,

significant differences in contributions to carbon stock estimation are determined by stand height (Darlina et al., 2023).

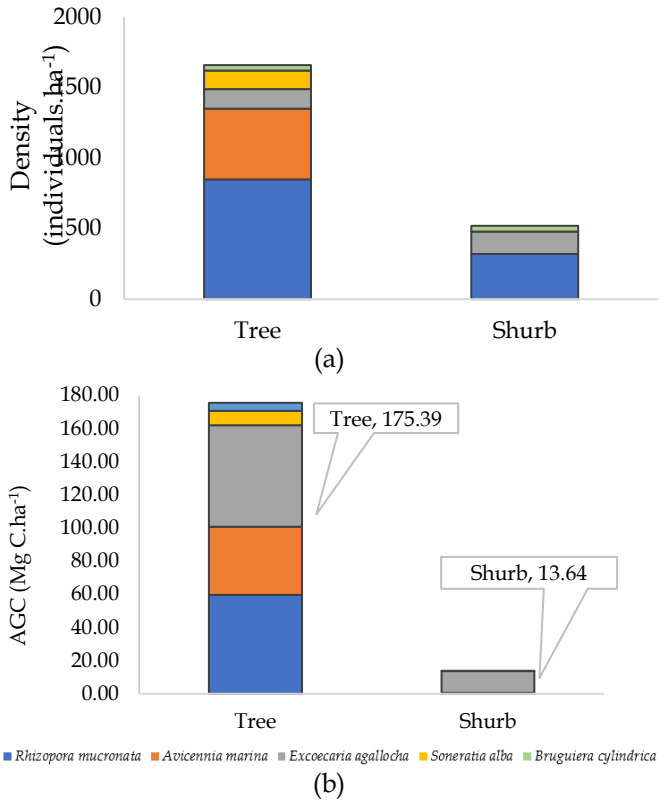


Figure 3. The density of trees and shrubs (a) and the aboveground carbon stock (b) of Banyuglugur mangrove, as contributed by various observed species.

As predicted by the InVEST model, from 2018 to 2025 indicates the recovery and expansion of mangrove cover, a condition commonly observed in regenerating mangrove ecosystems (Tran, Reef, Zhu, & Mohan, 2025). This finding suggests that the Banyuglugur mangrove ecosystem functions effectively as a carbon sink, consistent with global studies on the dynamics of carbon accumulation in regenerating mangroves (Sitthi et al., 2025). However, the InVEST value in 2025 shows an overestimation compared to field measurements. This aligns with several studies that highlight the limitations of spatial models when not calibrated with the characteristics of the local stand structure, as these models generally assume homogeneous vegetation within each land-cover (Yang et al., 2025), leading to potential bias in carbon stock assessments. Therefore, adjustments to biomass parameter values, integration of field data, and model calibration are needed to improve the accuracy of carbon estimation in mangrove ecosystems. Wang et al. (2024) found that the results of InVEST calculations are often higher than those of other models, such as CASA, leading to a significant quantitative difference.

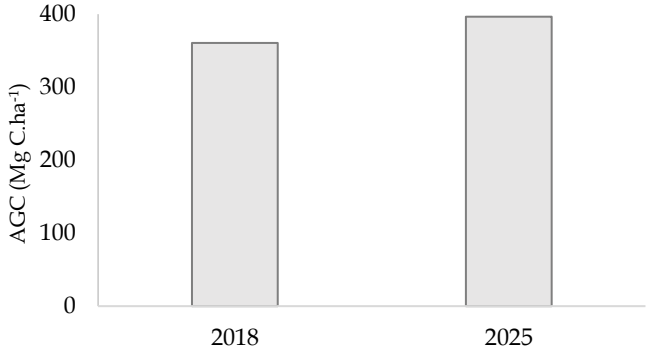


Figure 4. The dynamics of AGC estimation based on InVEST

Relationship between NDVI and Canopy Cover and Aboveground Carbon Stock

The regression analysis results show that NDVI ($p = 0.589$; $R^2 = 0.05$) and canopy cover ($p = 0.49$; $R^2 = 0.39$) are not significantly related to AGC. Spearman correlation also shows a weak and non-significant relationship ($p > 0.05$), but the regression coefficient indicates a positive trend ($\beta > 0$) (Figure 5). These findings suggest that variations in AGC cannot be fully attributed to changes in canopy cover or NDVI.

The discrepancy between the extent of canopy cover and the high AGC suggests that the relationship between these two variables is indirect and insignificant. This confirms that canopy cover is not the sole indicator representing mangrove biomass. Species composition and stem size are key determining factors, as species with larger stem diameters, such as *E. agallocha*, are able to store more carbon even if the canopy cover is not dominant. Conversely, the dominance of *R. mucronata*, which has dense branching and wider leaves, can result in high canopy cover values without a significant increase in biomass (Rukminasari et al., 2025). This finding reinforces that vegetation structure, which more accurately reflects the amount of carbon stock in the mangrove ecosystem.

The relatively weak relationship between NDVI, canopy cover, and AGC highlights the limitations of spectral indicators in capturing biomass variation. The NDVI value indeed reflects the greenness level of vegetation (Simarmata et al., 2021) and is typically associated with canopy density; however, it does not consistently represent the biomass stored. Structural factors, such as wood diameter, proved to be more determinant of carbon accumulation, indicating that large-diameter vegetation can have high carbon stocks despite low density (Slik et al., 2013). NDVI is prone to saturation in extremely dense canopies and is influenced by seasonal fluctuations and canopy heterogeneity, suggesting that fluctuations in vegetation structure are not adequately represented. Environmental factors, including soil fertility and tree density, have a significant influence on biomass potential. Consequently, carbon

stock assessment necessitates the amalgamation of field data with remote sensing data to enhance the accuracy and objectivity of the interpretation (Arief et al., 2025).

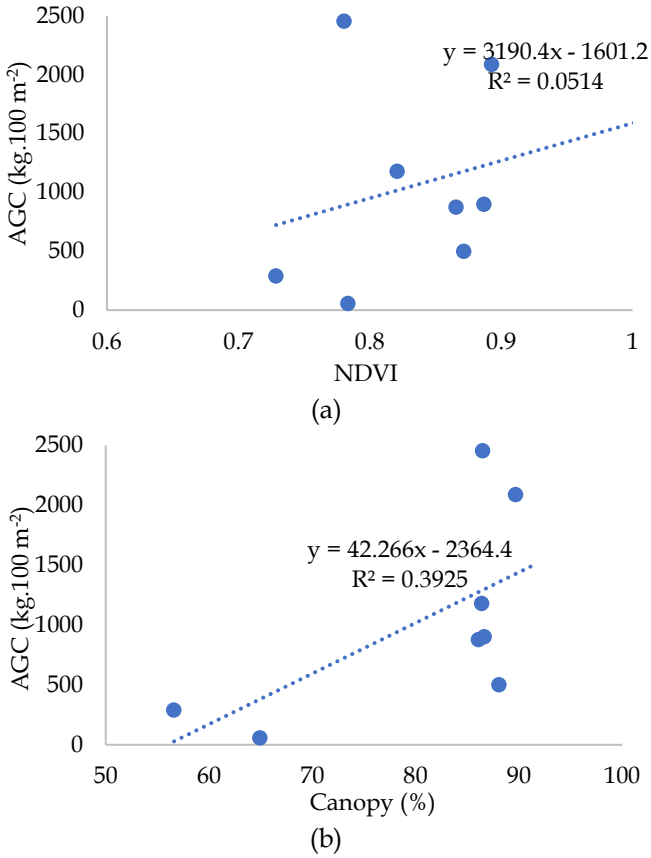


Figure 5. Relationship between canopy cover (a) and NDVI (b) with aboveground carbon stock

Conclusion

The Banyuglugur mangrove ecosystem experienced an increase in canopy cover and mangrove area of 4.12% between 2018 and 2025, indicating ecosystem regeneration and stability. The estimated AGC based on field measurements in 2025 is 189.03 Mg C/ha, with the largest contribution coming from the species *R. mucronata* and *E. agallocha*. The InVEST model predicts an increase in carbon stock as mangrove area increases; however, it produces values that are significantly higher than those observed in field measurements. Analysis of the relationship reveals that NDVI and canopy cover are not significantly related to AGC, although they exhibit a positive trend, which supports the conclusion that mangrove carbon accumulation is more influenced by vegetation structure.

Acknowledgements
The authors gratefully acknowledge the Faculty of Mathematics and Natural Sciences, Universitas Brawijaya, for financial support through the Hibah Penelitian B 2025 scheme No. 06455.25/UN10.F0901/B/PT/2025. Special appreciation is extended to Anatasya N. Aprilia and Sandrina Z. Jahja for their valuable support during field data collection and data processing. We also acknowledge Ecology Team and all individuals who contributed to this study but could not be mentioned individually.

Author Contributions
All authors have read and agreed to the published version of the manuscript. The final article was reviewed and approved by all contributors.

Funding
This research received no external funding.

Conflicts of Interest
The authors declare no conflict of interest.

References

Andiani, A. A. E., Karang, I. W. G. A., Putra, I. N. G., & Dharmawan, I. W. E. (2021). Hubungan Antar Parameter Struktur Tegakan Mangrove Dalam Estimasi Simpanan Karbon Aboveground pada Skala Komunitas. *Jurnal Ilmu dan Teknologi Kelautan Tropis*, *13*(3), 483–496. https://doi.org/10.29244/jitkt.v13i3.36363

Aprilita, D., Supratman, O., & Farhaby, A. M. (2024). Estimasi Stok Karbon Ekosistem Mangrove Sebagai Upaya Pengelolaan Blue Carbon di Desa Riding Panjang Kabupaten Bangka. *Jurnal Laut Khatulistiwa*, *7*(3), 173–189. https://doi.org/10.26418/lkuntan.v7i3.81929

Arfan, A., Sanusi, W., & Rakib, M. (2023). Analisis Kerapatan Mangrove dan Keanekaragaman Makrozoobenthos di Kawasan Ekowisata Mangrove Lantebung Kota Makassar. *Journal of Marine Research*, *12*(3), 493–500. https://doi.org/10.14710/jmr.v12i3.38060

Arief, M. C. W., Albert, K., Surahmat, R. J., Nugraha, R. R. Y., Muslimah, K., & Kelana, P. P. (2025). Analysis of Canopy Cover and Estimation of Carbon Storage Potential in Mangrove Vegetation on Rakit Island, Indramayu Regency. *Egyptian Journal of Aquatic Biology and Fisheries*, *29*(4), 2545–2559. https://doi.org/10.21608/ejabf.2025.448433

Darlina, I., Wilujeng, S., & Nurmajid, F. (2023). Estimasi Cadangan Karbon Dan Serapan Karbon di Taman Maluku Kota Bandung. *Paspalum: Jurnal Ilmiah Pertanian*, *11*(1), 163. https://doi.org/10.35138/paspalum.v11i1.556

Dewi, Y., Leksono, A., Retnaningdyah, C., & Arisoesilaningsih, E. (2023). Evaluating the Waterbirds Diversity and Its Preys Under Different Mangrove Ecosystem in The Situbondo Coast, East Java. *IOP Conference Series: Earth and Environmental*

Science, *1191*(1), 012009. https://doi.org/10.1088/1755-1315/1191/1/012009

Dharmawan, I. W. (2020). *Hemispherical Photography Analisis Persentase Tutupan Kanopi Komunitas*. Nas Media Pustaka.

Dharmawan, I. W. S. (2010). Pendugaan Biomasa Karbon di Atas Tanah Pada Tegakan Rhizophora Mucronata di Ciasem, Purwakarta. *Jurnal Ilmu Pertanian Indonesia*, *15*(1), 50–56.

Dharmawan, I. W. S., & Siregar, C. A. (2008). *Karbon Tanah dan Pendugaan Karbon Tegakan Avicennia marina (Forsk.) Vierh. Di Ciasem, Purwakarta*. *5*(4), 317–328.

Heumann, B. W. (2011). Satellite remote sensing of mangrove forests: Recent advances and future opportunities. *Progress in Physical Geography: Earth and Environment*, *35*(1), 87–108. https://doi.org/10.1177/0309133310385371

Istomo, Hartoyo, A. P. P., & Fitriansyah, M. R. (2025). Korelasi Cadangan Karbon terhadap Kerapatan Vegetasi Berdasarkan NDVI di Zona Rehabilitasi Taman Nasional Gunung Halimun Salak. *Journal of Tropical Silviculture*, *16*(01), 1–8. https://doi.org/10.29244/j-siltrop.16.1.1-8

Komiyama, A., Poungparn, S., & Kato, S. (2005). Common allometric equations for estimating the tree weight of mangroves. *Journal of Tropical Ecology*, *21*(4), 471–477. https://doi.org/10.1017/S0266467405002476

Ma, T., She, Y., Zhao, L., Hu, B., Feng, X., Zhao, J., & Zhao, Z. (2022). Alpine Wetland Evolution and Their Response to Climate Change in the Yellow-River-Source National Park from 2000 to 2020. *Water*, *14*(15), 2351. https://doi.org/10.3390/w14152351

Mulyana, B., Purwanto, R. H., Intan Sari, P., Faqih Hidayatullah, M., Atika Marpaung, A., Satria Raditya Putra, I., & Dwika Putra, A. (2021). The environmental services of Pangarengan mangrove forest in Cirebon, Indonesia: Conserving biodiversity and storing carbon. *Biodiversitas Journal of Biological Diversity*, *22*(12). https://doi.org/10.13057/biodiv/d221246

Natural Capital Alliance. (n.d.). *InVEST Software & Data*. Retrieved October 20, 2026, from https://naturalcapitalalliance.stanford.edu/software/invest

Purwanto, A. D., & Asriningrum, W. (2019). Identification of Mangrove Forests Using Multispectral Satellite Imageries. *International Journal of Remote Sensing and Earth Sciences*, *16*(1), 63–86.

Rafsenja, U., Golok Jaya, L. Muh., Sawaludin, & Rahim, S. (2020). *Analisis Perbandingan Citra Landsat 8 dan Citra Sentinel 2-A untuk Mengidentifikasi Sebaran Mangrove*. *4*(1). https://doi.org/10.5281/ZENODO.3875970

Rahmi, S., Rustam, R., & Yusuf, K. (2025). Struktur Vegetasi Mangrove Berdasarkan Tekstur Substrat Didusun Sabang Desa Bonto Bahari Kecamatan Bontoa Kabupaten Maros. *JURNAL ILMIAH WAHANA LAUT LESTARI (JIWaLL)*, *2*(2), 167–179. https://doi.org/10.33096/jiwall.v2i2.508

Rukminasari, N., Kadir, A., Kudsiah, H., & Yunus, B. (2025). Comparison of Structure and Composition of Mangrove Types in Bonto Bahari and Ampekalle Area, Maros Regency. *Jurnal Ilmu Kelautan SPERMONDE*, 12–18. https://doi.org/10.35911/jiks.v11i1.44591

Sasmito, S. D., Kuzyakov, Y., Lubis, A. A., Murdiyarso, D., Hutley, L. B., Bachri, S., Friess, D. A., Martius, C., & Borchard, N. (2020). Organic carbon burial and sources in soils of coastal mudflat and mangrove ecosystems. *CATENA*, *187*, 104414. https://doi.org/10.1016/j.catena.2019.104414

Sholeh, S., Evianovita, D. I. N., Mayasari, A. Y., & Sudewo, A. A. (2024). The Role of the Community in the Development of Mangrove Forest Ecotourism in Pasar Banggi, Rembang Regency. *Indonesian Journal of Environment and Disaster*, *3*(1), 121–132. https://doi.org/10.20961/ijed.v3i1.1207

Simarmata, N., Wikantika, K., Tarigan, T. A., Aldyansyah, M., Tohir, R. K., Fauziah, A., & Purnama, Y. (2021). Analisis Transformasi Indeks Ndvi, Ndwi Dan Savi Untuk Identifikasi Kerapatan Vegetasi Mangrove Menggunakan Citra Sentinel Di Pesisir Timur Provinsi Lampung. *JURNAL GEOGRAFI Geografi Dan Pengajarannya*, *19*(2), 69–79. https://doi.org/10.26740/jggp.v19n2.p69-79

Sitthi, A., Pimple, U., Piponiot, C., & Gond, V. (2025). Assessing the Effectiveness of Mangrove Rehabilitation Using Above-Ground Biomass and Structural Diversity. *Scientific Reports*, *15*(1), 7839. https://doi.org/10.1038/s41598-025-92514-7

Slik, J. W. F., Paoli, G., McGuire, K., Amaral, I., Barroso, J., Bastian, M., Blanc, L., Bongers, F., Boundja, P., Clark, C., Collins, M., Dauby, G., Ding, Y., Doucet, J., Eler, E., Ferreira, L., Forshed, O., Fredriksson, G., Gillet, J., … Zweifel, N. (2013). Large trees drive forest aboveground biomass variation in moist lowland forests across the tropics. *Global Ecology and Biogeography*, *22*(12), 1261–1271. https://doi.org/10.1111/geb.12092

Suhardi, R. M., Rahardi, W., Shih, H.-C., Mantiquilla, J. A., Wu, Y.-H., Shiao, M.-S., & Chiang, Y.-C. (2024). A review of the mangrove ecosystem in Indonesia: Biodiversity, conservation, and challenges in sustainable management. *Ecological Genetics and*

Genomics, *32*, 100282. https://doi.org/10.1016/j.egg.2024.100282

Sunkur, R., Kantamaneni, K., Bokhoree, C., Rathnayake, U., & Fernando, M. (2024). Mangrove mapping and monitoring using remote sensing techniques towards climate change resilience. *Scientific Reports*, *14*(1), 6949. https://doi.org/10.1038/s41598-024-57563-4

Wu, Y., Lu, C., Wu, K., Gao, W., Yang, N., & Lin, J. (2025). Advancements and trends in mangrove species mapping based on remote sensing: A comprehensive review and knowledge visualization. *Global Ecology and Conservation*, *57*, e03408. https://doi.org/10.1016/j.gecco.2025.e03408

Yang, X., Wang, C., Liu, C., Liu, Z., Liu, B., & Xu, C. (2025). Assessing the spatio evolution of carbon sequestration and optimizing ecological restoration strategies using the InVEST model: A case study of the Yellow River Estuary, China. *Marine Environmental Research*, *209*, 107204. https://doi.org/10.1016/j.marenvres.2025.107204

Zhu, Y., Jia, P., Zhang, Z., Cheng, J., & Wang, N. (2024). Carbon Storage Assessment under Mangrove Restoration of Dongzhai Harbor in Hainan Island, China. *Ecosystem Health and Sustainability*, *10*, 0257. https://doi.org/10.34133/ehs.0257