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MANGROVE CARBON BIOMASS POTENCY THROUGH SATELLITE IMAGE ANALYSIS IN THE EASTERN AREA OF MAUMERE BAY

POTENSI BIOMASSA KARBON EKOSISTEM MANGROVE MELALUI ANALISIS CITRA SATELIT DI KAWASAN TIMUR TELUK MAUMERE

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ABSTRACT

Mangrove ecosystems can store significant amounts of carbon in their standing biomass. The eastern part of Maumere Bay contains mangrove areas that are important because of their economic and ecological value. The amount of carbon stored in the mangroves is unknown due to the lack of inventory data. The objective of this study is to obtain estimated surface carbon biomass stocks in the mangrove forests in the eastern part of Maumere Bay using Sentinel-2A imagery. The study was conducted from June to September 2024. Carbon stock values were obtained using the Normalized Difference Vegetation Index (NDVI) analysis method. Actual carbon stocks in surface biomass were obtained from the allometric equation. A stratified sampling method was applied to determine 18 sample spots, each with a size of 10×10 m^2. Data was analyzed using accuracy tests and linear, polynomial, and exponential regression. The results of the regression analysis show that the exponential regression equation has the highest coefficient of determination (R^2) value, namely 0.8373, with the highest accuracy. Therefore, the exponential regression equation was accepted as a model for estimating surface carbon stocks. The NDVI vegetation index has a strong correlation with carbon stocks of 83.73% (R^2 = 0.8373). The exponential equation is $y = 13.637e^{2.0499x}$, which reflects natural growth patterns where y is the carbon value and x is the NDVI value. The mangrove area covers 527.93 ha. The total aboveground carbon stock amounts to 29,760.52 tons of carbon, with an average value of 56.34 tons of carbon per hectare.

Keywords: carbon, mangrove, Maumere Bay, satellite

ABSTRAK

Ekosistem mangrove dapat menyimpan banyak karbon pada biomassa tegakan. Bagian timur Teluk Maumere memiliki kawasan mangrove yang sangat penting untuk dijaga demi memelihara nilai ekonomis dan ekologisnya. Jumlah karbon yang tersimpan pada mangrove belum diketahui karena tidak ada data inventarisasi. Tujuan penelitian adalah untuk mendapatkan data estimasi cadangan biomassa karbon permukaan pada hutan mangrove di bagian timur Teluk Maumere, menggunakan citra Sentinel-2A. Penelitian dilakukan pada Juni hingga September 2024. Nilai cadangan karbon diperoleh dari metode analisis NDVI (*Normalized Difference Vegetation Index*). Cadangan karbon aktual biomass permukaan diperoleh dari persamaan alometrik. Metode sampel *stratified* digunakan untuk menentukan 18 titik sampel, yang berupa plot berukuran 10×10 m^2. Analisis data dilakukan dengan menggunakan uji akurasi, linear, polinomial, dan regresi eksponensial. Hasil analisis regresi menunjukkan bahwa persamaan regresi eksponensial memiliki nilai koefisien determinasi (R^2) tertinggi, yaitu 0,8373 dengan nilai akurasi tertinggi. Oleh karena itu, persamaan regresi eksponensial diterima sebagai model penduga stok karbon permukaan. Indeks vegetasi NDVI memiliki korelasi yang kuat dengan cadangan karbon sebesar 83,73% (R^2 = 0,8373). Persamaan eksponensial $y = 13{,}637e^{2{,}0499x}$ yang mencerminkan pola pertumbuhan alami dengan y adalah nilai karbon dan x adalah nilai NDVI. Luas hamparan mangrove sebesar 527,93 ha. Total cadangan karbon di atas permukaan mencapai 29.760,52 ton karbon, dengan nilai rata-rata 56,34 ton karbon per ha.

Kata kunci: karbon, mangrove, satelit, Teluk Maumere

INTRODUCTION

The need for monitoring carbon has increased in response to climate change, a natural phenomenon linked to global warming and greenhouse gases. This need for carbon information continues to increase due to increasing levels of carbon dioxide (CO_2) in the atmosphere caused by both direct and indirect human activities. The emission of he reduction of atmospheric greenhouse gases, such as CO_2, could be reduced by the absorption of CO_2 by plants during photosynthesis and the storage of carbon in plant organs (sequestration), both of which contribute to reducing the rate of global warming and the greenhouse effect (Hasibuan *et al.* 2020).

Mangroves can serve as a solution to address global warming due to their crucial role in absorbing and storing carbon. Mangroves have a greater carbon storage capacity than other terrestrial forests. The amount of carbon stored by mangrove forests can be up to five times that of tropical rainforests as a whole (Nellemann *et al.* 2009; Marzuki *et al.* 2023). Mangroves function as a sustainable carbon sequestrator through photosynthesis and carbon storage in tree biomass (Waru *et al.* 2022). However, the extent of carbon biomass reserves in mangrove stands, particularly in the eastern part of Maumere Bay of Sikka Regency, East Nusa Tenggara Province, remains unknown. This data illustrates the important role of mangroves in the eastern part of the Bay ecologically and economically, as well as in mitigating global warming and reducing the greenhouse effect.

Maumere Bay is located on the north coast of Sikka Regency in East Nusa Tenggara (NTT) Province. Mangrove forests stretch from Magepanda District in the west to Talibura District in the east, along with small islands within Maumere Bay. Maintaining and preserving the mangrove forests in Maumere Bay is crucial due to their significant environmental and economic benefits. Meanwhile, it is not known how much carbon actually exists in the mangrove forests because there is no inventory data. The NTT region, which borders Timor-Leste, urgently needs to improve its security, socio-cultural, and economic aspects to improve community well-being and reduce the risk of environmental damage. This is especially true for environmentally based economies.

The amount of carbon stocks in a mangrove area can be determined through field biomass measurements (terrestrial methods). While this can provide highly accurate results, it is time-consuming, expensive, and labor-intensive to conduct comprehensive studies. Rapid advances in remote sensing have enabled technology to overcome these obstacles. The thirteen-band multispectral sensor on the Sentinel-2A satellite can collect detailed vegetation information (Waru *et al.* 2022). Therefore, a mathematical model (linear, polynomial, and exponential regression) is needed that can connect NDVI values with real carbon stocks in the field to determine the best model for estimating mangrove carbon stocks.

The purpose of this study is to obtain estimated carbon biomass reserves in the form of tons of carbon per hectare (tons C/ha) in mangrove forests in eastern Maumere Bay, including the islands of Kojadoi, Talibura, Darat Pantai, and Nangahale, using Sentinel-2A imagery, based on the results of the Normalized Differential Vegetation Index (NDVI) approach integrated with field-based allometric carbon data through linear, polynomial, and exponential regression models. This method provides faster, more efficient results and can be an alternative for estimating carbon storage in mangrove ecosystems. Carbon biomass reserve inventory data is necessary for further mangrove ecosystem management and other development policies.

This study differs from previous studies by Waru *et al.* (2022) and Marzuki *et al.* (2023), which used Sentinel-2A imagery, ENVI (Environment for Visualizing Images) software, which has the advantage of providing various tools to meet needs, the Normalized Differential Vegetation Index (NDVI) formula, carbon stock values based on in-situ data (tree diameter, mangrove species, canopy percentage), and the NDVI formula. Models were constructed using polynomial and exponential regression. The study location was Maumere Bay, Sikka Regency of East Nusa Tenggara Province, where no inventory data on mangrove carbon reserves were available.

METHODS

Times and location

The research was conducted in Maumere Bay in Sikka Regency, East Nusa Tenggara (NTT) Province. Kojadoi Island, Talibura, Darat Pantai, and Nangahale are natural mangrove areas. The research, which ran from June to September 2024, involved a literature review, satellite imagery processing, field data collection, data processing, and the development of research findings.

Fieldwork began with the determination of 18 sample plots selected from different land unit classes to represent conditions across the entire study area. Figure 1 shows the 18 sample points, representing very dense, moderate, and sparse cover, were placed on a 10×10 m^2 grid, based on the Normalized Differential Vegetation Index (NDVI) approach. These sample points represented specific NDVI values (high, moderate, and low), so the analysis results reflected the vegetation conditions throughout the mangrove forest area.

Equipment and supplies

Measuring tape, stakes, rope, fisheye cameras, GPS, and ship transportation were some of the equipment and facilities used in this research. Microsoft Excel, ArcGIS 10.8, ImageJ, and ENVI 5.2 were some of the data processing programs.

Data collection

The data collected consisted of Sentinel-2A satellite imagery. On July 14, 2024, Sentinel-2A acquired images for the Kojadoi Island area, while on July 16, 2024, it acquired images for the Nangahale, Talibura, and Darat Pantai areas. The images were acquired from the official Copernicus Open Access Hub platform, which has 13 spectral bands. The selected images were of good quality and clarity, taken on clear, clear days without dense clouds to minimize distortion caused by pollution or high humidity. Photos were taken in the morning, with better lighting angles, allowing for accurate monitoring and analysis.

In situ field data collection included mangrove trees, whose trunk circumference was measured at breast height at a height of approximately 130 cm, which is necessary to calculate tree diameter. In addition, species identification and a count of mangrove trees were conducted. Field data collection was conducted at 18 representative points, each consisting of a 10×10 m (100 m^2) plot representing each pixel in the Sentinel-2A image. The results of the field data collection included data on mangrove tree trunk circumference, diameter, type, and number of mangrove trees.

Substrate type data collection was conducted by manually collecting sediments, then identifying the color, texture, and odor of the sediment samples were carried out. Subsequently, the samples were categorized as sand, mud, or a mixture of sand and mud (Rahmawati *et al.* 2014).

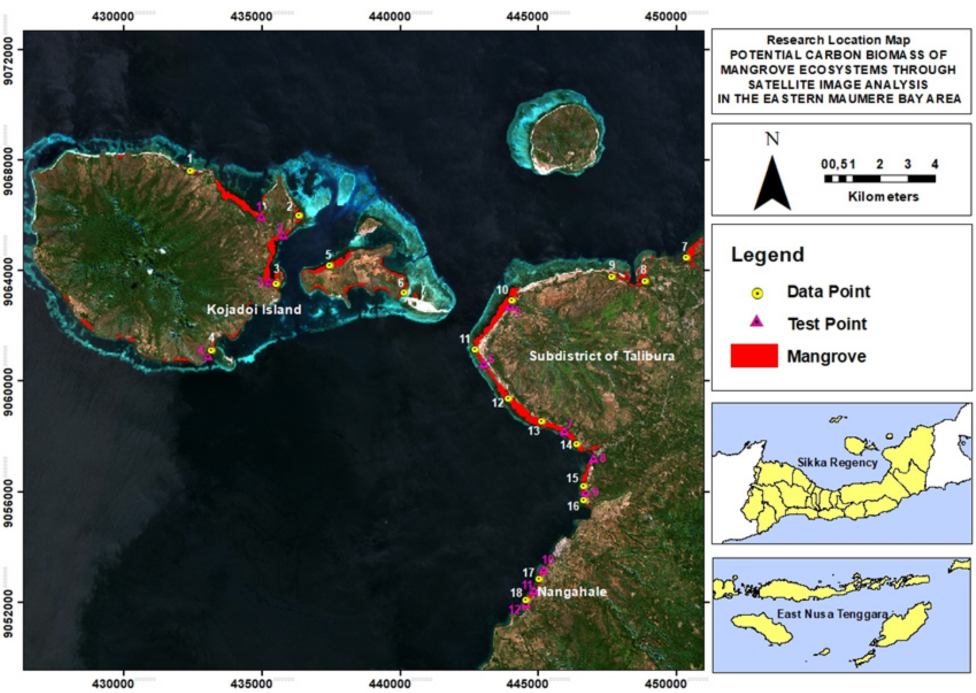

Figure 1. Research location in eastern Maumere Bay, East Nusa Tenggara (18 plots).

Image processing

Sentinel-2A imagery was processed using ENVI 5.2, and the results were displayed using ArcGIS 10.8. Sentinel-2A imagery has several advantages, such as high spatial resolution, 13-band multisensor spectrum – available red, NIR (near infrared), and SWIR (shortwave infrared) channels, which are very suitable for calculating vegetation indices such as NDVI, which is used as an estimate of carbon stocks, free and easily accessible, wide coverage, and has temporal continuity.

Sentinel-2A imagery was processed through geometric correction, radiometric correction, band merging, and cropping. Geometric correction ensures that the satellite imagery is in geographic coordinates, and radiometric correction removes noise from the position of the sun. Cropping is the process of cutting an image to remove unnecessary areas and focus on a specific area of interest. Band merging is performed to display mangroves in the imagery and facilitate the differentiation between mangroves and other vegetation. Distinguishing between mangroves and other vegetation is easier using a false color approach. According to Arhatin and Wahyuningrum (2013), the composite image (the result of band merging) shows primary mangroves in dark red, secondary mangroves in bright red, terrestrial vegetation in orange, water in dark blue to black, and settlements in green. The composite image consists of bands 2, 3, 4, 8, and 11.

The composite image was converted into mangrove spatial element classes using maximum likelihood classification to obtain the mangrove distribution. The mangrove distribution area was then transformed into the Normalized Difference Vegetation Index (NDVI) equation to display the classification of mangrove density classes, using the formula of Huete *et al.* (1999).

$$NDVI = \frac{(NIR - R)}{(NIR + R)}$$

Description:
NDVI = Normalized Difference Vegetation Index
NIR = Near IR band spectral reflectance values
R = Spectral reflectance values in the red band

The results of the reclassification are then subjected to a masking process, which limits the area of mangrove vegetation so that the calculation of carbon stocks is limited only to areas consisting of mangrove vegetation.

Carbon stock

The results of field data collection on 18 plots, namely the diameter, type, and number of mangrove trees, were used to calculate mangrove biomass, using allometric equations as shown in Table 1. Each type of mangrove has a different allometric equation, according to the results of previous expert research. The allometric equations shown in Table 1 are adjusted to the types of mangroves found in eastern Maumere Bay.

The specific gravity (ρ) values of mangroves according to Simpson (1996), which are required to be included in each allometric equation used, are presented in Table 2.

Table 1. Allometric equations of several types of mangroves found in eastern Maumere Bay.

No.	Mangrove Species	Allometric Equations	Sources
1	*Avicennia alba*	$B = 0.079211 (D)^{2.470895}$	Tue *et al.* (2014) in Marzuki *et al.* (2023).
2	*A. marina*	$B = 0.1848 (D)^{2.3624}$	Dharmawan and Siregar (2008).
3	*Rhizophora apiculata*	$B = 0.043 (D)^{2.63}$	Amira (2008) in Marzuki *et al.* (2023).
4	*R. mucronata*	$B = 0.1466 (D)^{2.3136}$	Dharmawan (2010) in Marzuki *et al.* (2023).
5	*Sonneratia alba*	$B = 0.3841 (D)^{2.101} * \rho$	Kauffman and Cole (2010) in Marzuki *et al.* (2023).
6	*Bruguiera gymnorrhiza*	$B = 0.0754 (D)^{2.505}$	Kauffman and Donato (2012) in Marzuki *et al.* (2023).

Description:
B = Biomass (kg/m^2)
ρ = Specific gravity of plants (g/cm^3)
D = Diameter at chest height (cm)

Table 2. Some specific gravity of mangrove wood in eastern Maumere Bay.

No.	Mangrove Species	Wood Specific Gravity (g/cm^3)
1	*Avicennia officinalis*	0.670
2	*A. marina*	0.661
3	*Rhizophora apiculata*	1.050
4	*R. mucronata*	0.867
5	*Sonneratia alba*	0.780
6	*Bruguiera gymnorrhiza*	0.741

Source: Simpson (1996)

The actual biomass value of mangroves is used to calculate the carbon stock value of mangroves. Carbon is present in 50% of the vegetative biomass (Rahmattin dan Hidayah 2020; Mutmainna *et al*. 2024).

$$C = \frac{1}{2} \times B$$

Description:
C = Carbon content (kg/m^2)
B = Biomass (kg)

The National Standardization Agency (2011) is used as a reference in converting carbon stocks into tonnes, using the following formula:

$$C_n = \frac{C_x}{1{,}000} \times \frac{10{,}000}{L_{plot}}$$

Description:
C_n = Carbon stock per hectare (ton/ha)
C_x = Carbon stock in each plot (kg)
L_{plot} = Plot area (m^2)

Percentage of canopy cover

The calculation of canopy cover percentage used hemispherical photography, in this case, using a fisheye camera. Each mangrove plot was divided into 4-9 subplots. In each subplot, the camera was positioned at chest height and facing the sky, and photographs were taken. The resulting photographs were analyzed for mangrove canopy cover percentage using Microsoft Excel and ImageJ (Dharmawan and Pramudji 2017).

Based on the color differences between sky pixels (white) and mangrove vegetation (black), canopy cover percentage was calculated using binary image analysis (Chianucci and Cutini 2012; Kassagi *et al.* 2024):

$$\%\, Tutupan\ (cover)\ mangrove = \frac{P255}{\sum P} \times 100$$

Description:
$P255$ = Interpretation of mangrove canopy cover with a pixel count of 255
ΣP = Total number of pixels

Regression analysis

A correlation analysis using the Pearson correlation method was performed before the regression analysis to determine the strength of the relationship between variables. Next, a simple linear regression analysis was conducted to determine the extent to which the independent variables adequately explain the dependent variable. This linear regression analysis was conducted to determine the relationship between (1) carbon stocks and the NDVI vegetation index value, (2) carbon stocks and the percentage of canopy cover, and (3) the percentage of canopy cover and the NDVI vegetation index value.

The carbon stock estimation model used three types of regression equations: simple linear regression, polynomial regression, and exponential regression. The carbon stock estimation model was selected from among these three regression models, namely the one that produced the highest coefficient of determination.

Accuracy test

Accuracy testing was conducted by comparing preprocessed image data with field data. The accuracy test used 12 different plot points out of the 18 plot points used in the field data collection. These 12 plot points represented very dense, moderate, and sparse cover divisions, considering efficiency while maintaining the objectivity of the research results. The positions of the 12 plot points for the accuracy test are shown in Figure 1. Accuracy testing can avoid bias that might occur if using the same plot points as the field data collection. This can increase the objectivity of the analysis results, because they are not affected by the same data used in the field data collection. Thus, it can test the generalization ability of the model or algorithm used in satellite image processing.

Accuracy testing was conducted using the Root Mean Square Error (RMSE) method. According to Xu *et al.* (2024a), the smaller the error that occurs when using the model, the lower the RMSE value, using the following formula:

$$RMSE = \frac{\sqrt{\sum(yi - yi')^2}}{n}$$

Description:
RMSE = Root Mean Square Error Value
yi = Measurement value
yi' = Estimated value
n = Number of samples

RESULTS AND DISCUSSION

Mangrove density based on the NDVI value

The results showed NDVI values ranging from 0.35 to 0.92. Eastern Maumere Bay, consisting of Kojadoi Island, Talibura, Darat Pantai, and Nangahale, had a wide range of NDVI values. Kojadoi Island had NDVI values ranging from 0.52 to 0.92. Talibura and Darat Pantai had NDVI values between 0.35 and 0.90, and Nangahale had NDVI values between 0.70 and 0.82. The data collected ranged between 0 and +1. Higher NDVI values indicate higher canopy cover and mangrove density.

Based on the NDVI transformation results, lower NDVI values are indicated by greater red color, while higher NDVI values are indicated by greater green color. The mangrove vegetation density can be seen in Figure 2 (a, b, c).

Composition of mangrove species

Six mangrove species were found in eastern Maumere Bay: *Avicennia alba*, *Avicennia marina*, *Rhizophora apiculata*, *R. mucronata*, *Sonneratia alba*, and *Bruguiera gymnorrhiza* (Figure 3). *Rhizophora apiculata* is the most abundant species in eastern Maumere Bay, with 182 stands across 18 plots: 57 stands on Kojadoi Island, 106 on Darat Pantai and Talibura, and 19 stands on Nangahale.

The species composition of mangrove vegetation exhibits a zonation pattern. Noor *et al.* (2006) stated that salinity levels, tidal influence, exposure (to waves), and soil type (mud, sand, or peat) are all related to the zonation pattern.

The composition of mangrove species in the eastern part of Maumere Bay differs between the three locations, namely on Kojadoi Island, where 6 species were found, on the Darat Pantai and Talibura, 4 species were found (*Avicennia marina*, *Rhizophora apiculata*, *R. mucronata*, *Sonneratia alba*), and on Nangahale, 3 species were found (*Avicennia marina*, *Rhizophora apiculata*, *Sonneratia alba*) as presented in Figure 3. The differences in the composition of mangrove species in the three locations can be attributed to differences in population density, where denser areas, such as Nangahale, put higher pressure on mangroves, thus reducing the number of species, and vice versa, on Kojadoi Island, with a sparse population, a higher number of species was found. The form of pressure on mangroves is higher in Nangahale, namely the development of settlements, port infrastructure, roads, and pollution, compared to Kojadoi Island, while the Darat Pantai and Talibura locations are in moderate condition. Muddy sand is the most common substrate found in the study location (Table 3).

Mangrove biomass, carbon content, canopy cover, and NDVI values

Based on the results of field surveys and image processing, the biomass, carbon content, canopy cover, and NDVI values of each plot were determined. Canopy cover conditions in eastern Maumere Bay were categorized as sparse to dense based on the cover criteria outlined in Ministerial Decree No. 201 of 2004. The percentage of canopy cover was 40.32% in plot 13 on Darat Pantai and Talibura, and 89.42% in plot 5 on Kojadoi Island, as presented in Table 3. Differences in canopy cover percentages between plots were caused by differences in the mangrove species that dominated the research plots and the density of trees that composed the plots. Pretzsch *et al.* (2015) stated that there is a positive relationship between actual leaf surface area and canopy cover, where the wider the canopy cover, the greater the leaf surface area available within it.

The substrate of each plot was silty sand. According to Noor *et al.* (2006), *Rhizophora* leaves are typically broad and measure 11–23 cm × 5–13 cm. *Rhizophora* fruits are viviparous, meaning they begin to develop while still on the parent tree. Propagules with pointed hypocotyls fall to the substrate close to the parent tree when they separate from it. A dense root structure is also found in other *Rhizophora* species (Noor *et al.* 2006). Consequently, there is often high canopy cover in dense *Rhizophora* communities. Compared to *Rhizophora* species, *Avicennia* and *Sonneratia* species tend to produce lower canopy cover due to their smaller leaf morphology and lower leaf density (Marzuki *et al.* 2023). The mangrove biomass in the eastern part of Maumere Bay, with the lowest value of 50.76 tons/hectare containing 25.38 tons/hectare of carbon, was found in plot 14 on the Darat Pantai and Talibura, while the highest mangrove biomass of 190.74 tons/hectare containing 95.37 tons/hectare of carbon was found in the plot on Kojadoi Island.

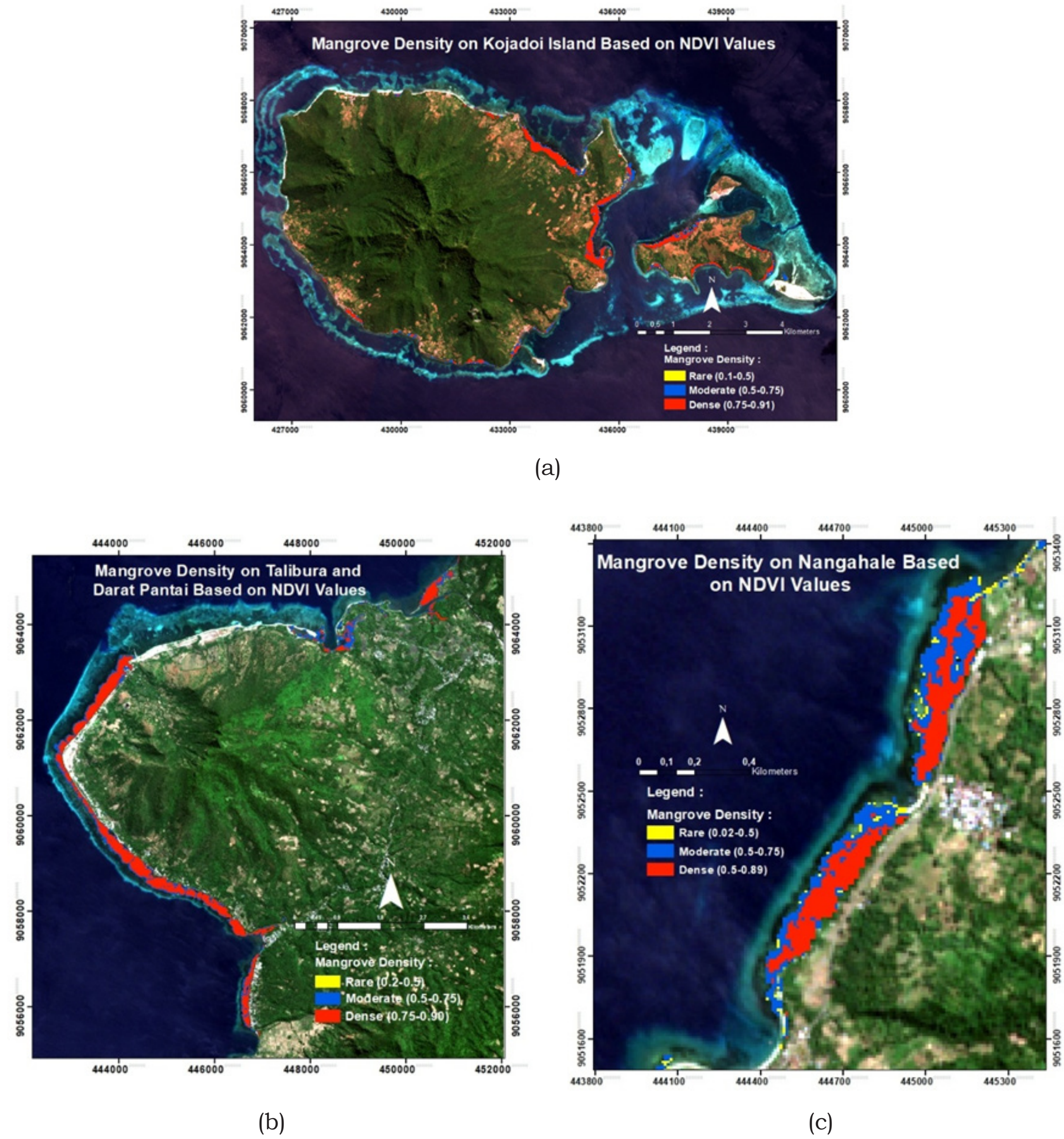

Figure 2. Mangrove density according to NDVI values in (a) Kojadoi, (b) Talibura/Darat Pantai, (c) Nangahale.

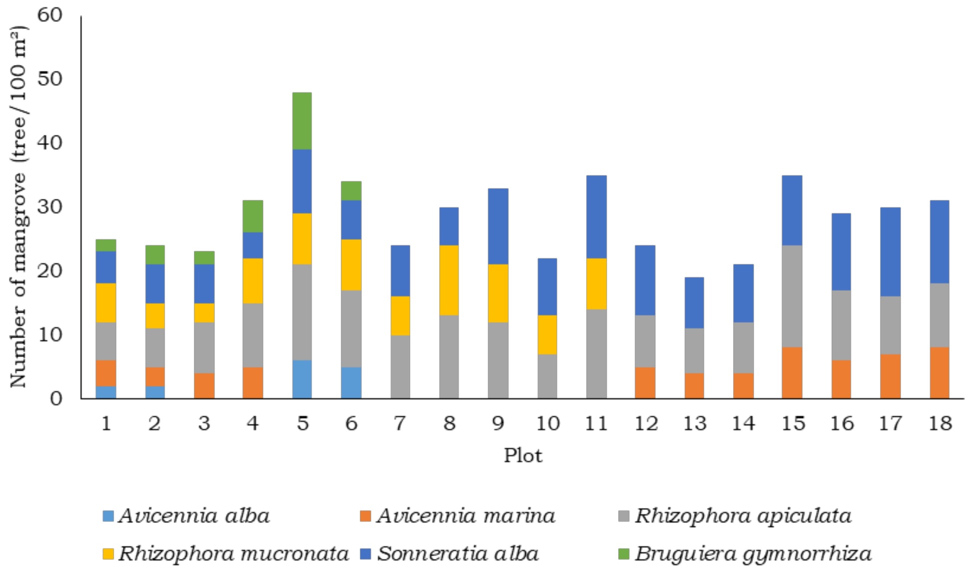

Figure 3. Composition of mangrove species (number of mangrove trees per species) in 18 plots.

Table 3. Mangrove tree biomass, carbon content in mangrove tree stands, and NDVI values in 18 research plots in eastern Maumere Bay.

Location	Plot	Biomass (ton/ha)	Carbon (ton/ha)	Canopy (%)	NDVI	Substrate
Kojadoi	1	145.46	72.73	70.65	0.854421	muddy sand
	2	138.24	69.12	71.23	0.763297	muddy sand
	3	112.55	56.275	65.82	0.698293	muddy sand
	4	73.85	36.925	55.37	0.509007	muddy sand
	5	190.74	95.37	89.42	0.917587	muddy sand
	6	125.23	62.615	76.58	0.815442	muddy sand
Talibura	7	98.45	49.225	75.52	0.829281	muddy sand
Darat Pantai	8	128.47	64.235	58.36	0.718315	muddy sand
	9	180.32	90.16	76.67	0.845236	muddy sand
	10	98.85	49.425	50.63	0.626564	muddy sand
	11	162.07	81.035	60.34	0.758131	muddy sand
	12	72.92	36.46	46.54	0.443427	muddy sand
	13	84.56	42.28	40.32	0.534997	muddy sand
	14	50.76	25.38	42.23	0.351863	muddy sand
	15	190.25	95.125	77.22	0.901265	muddy sand
	16	115.89	57.945	62.85	0.771854	muddy sand
Nangahale	17	145.28	72.64	74.63	0.81945	muddy sand
	18	134.41	67.205	65.24	0.703206	muddy sand

Regression analysis

The relationship between NDVI values and carbon

The relationship between NDVI and carbon values can be seen in Figure 4. The high NDVI value of 74.46% indicates a strong correlation between the NDVI and carbon values, which measure the quantity of carbon in tree stands, and the NDVI, which measures the greenness of the vegetation. In other words, a higher NDVI value indicates a higher carbon content in tree stands. This model cannot account for other variables not examined in this study, amounting to 25.54%, including tree species, tree age, and other environmental factors. The results of research by Xu *et al.* (2024b) stated that the lack of spatial distribution of tree age and species increases uncertainty in model estimates and makes it difficult to accurately predict carbon sequestration potential. Research by Withaningsih *et al.* (2024) in Jatigede, West Java, explains that landscape changes and spatial-temporal variations in aboveground are closely related to vegetation structure, stand age, and land-use changes.

The relationship between canopy cover and carbon

Figure 5 illustrates the relationship between canopy cover and carbon. Based on the coefficient of determination, 63.79% of the carbon value is influenced by canopy cover. The results of this study illustrate that the higher the percentage of canopy cover, the higher the mangrove carbon content. This is consistent with research by Khan *et al.* (2024), which found that changes in land cover and canopy density are directly related to changes in carbon stocks. They found that as canopy cover increases, the area's ability to store carbon also increases, especially in vegetation with older trees and more mature vegetation successional status.

The relationship between canopy cover and carbon content is positive: the wider and denser the canopy cover (vegetation), the greater the potential for carbon absorption, because the canopy plays a role in photosynthesis and storing organic carbon in plant biomass and soil, as well as holding back carbon emissions.

Relationship between NDVI and canopy cover

Figure 6 shows the relationship between NDVI values and canopy cover, where the NDVI value has an influence of 82.78% on the percentage of canopy cover. The influence of other factors not included in this study is 17.22%. The reflectance value of objects in satellite photos is used to calculate the NDVI value. Denser canopy cover, tree area, and tree diameter are all indicated by higher NDVI values. The amount of chlorophyll in the area will increase due to the canopy area. Higher NDVI values will result from increased green spectrum reflectance caused by higher chlorophyll content. Electromagnetic waves that cannot pass through the canopy can be reflected and captured by satellite sensors (Marzuki *et al.* 2023).

Carbon stock estimation model

The carbon stock estimation model is obtained from the regression equation between the dependent variable (pixel carbon value) and the independent variable (NDVI value). The pixel carbon value is obtained from the calculation of biomass and field carbon values covering only a 100 m^2 plot area. The carbon stock estimation model uses 3 types of regression equations: simple linear regression, polynomial regression, and exponential regression. The carbon stock estimation model was selected from the three regression forms, namely the one that produces the highest coefficient of determination value, as presented in Table 4.

Table 4 shows that the exponential regression equation produces the highest coefficient of determination (R^2) value, at 0.8373. The exponential regression equation was selected as the surface carbon stock estimation model, $y = 13.637e^{2.0499x}$, where y is the carbon value and x is the NDVI value. Figure 7 illustrates the relationship between NDVI and carbon values in the exponential regression model.

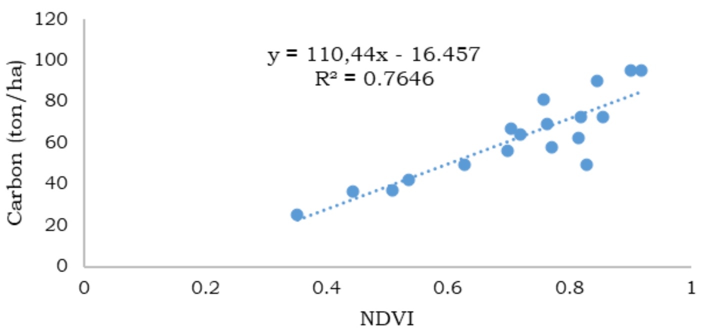

Figure 4. Linear regression relationship between NDVI values and carbon content from Sentinel-2A imagery.

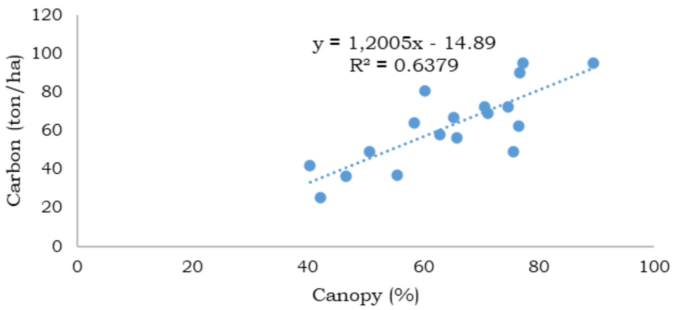

Figure 5. Linear regression relationship between canopy cover and carbon content from Sentinel-2A.

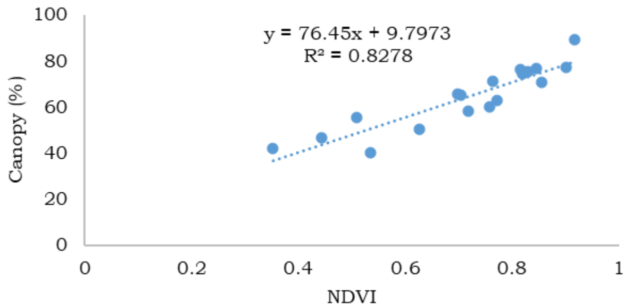

Figure 6. Linear regression relationship between NDVI values and canopy cover from Sentinel-2A imagery.

Table 4. Linear regression, polynomial regression, and exponential regression equations, as well as a comparison of the coefficient of determination (R^2) values of each regression equation.

Regression Equation	**R^2**
Linear:	
$y = 110.44x – 16.457$	$R^2 = 0.7646$
Polynomials (2nd order polynomials that form quadratic expressions):	
$y = 94.449x^2 – 11.972x + 20.464$	$R^2 = 0.7784$
Exponential:	
$y = 13.637e^{2.0499x}$	$R^2 = 0.8373$

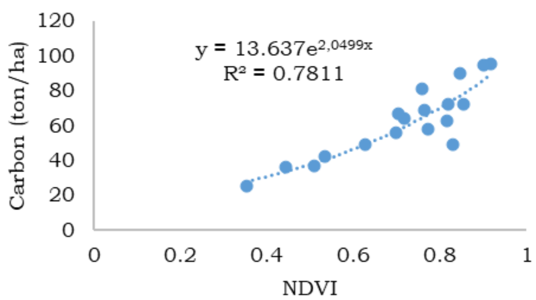

Figure 7. Exponential regression relationship of NDVI values with pixel carbon values from Sentinel-2A.

The results of this study also indicate that the area of mangroves in the eastern part of Maumere Bay is 527.93 hectares. Another study on the area of mangroves in Maumere Bay, namely by Vincentius *et al.* (2024), found that a mangrove expanse of 100.82 hectares was found in the western part of Maumere Bay; thus, the total area of mangroves in the entire Maumere Bay area (western and eastern parts) is 628.75 hectares. These data show an increase in the area of mangroves throughout the Maumere Bay area in 2024 compared to 2018. As stated by Vincentius *et al.* (2018), the area of mangroves in Maumere Bay is 564.32 hectares, stretching from Magepanda District in the west to Talibura District in the east. The increase in the area of mangroves is influenced by the impact of mangrove reforestation carried out by the community, together with related parties.

The accuracy test results yielded an accuracy value of 25.27, indicating that the carbon stock estimation model developed has a moderate bias value. This is because the carbon stock value is obtained from the calculation of the allometric equation for each mangrove species using tree trunk diameter as the estimated value. This accuracy value can be said to be close to zero, as it is closer to zero when compared to the results of research by Marzuki *et al.* (2023) on Nunukan Island, North Kalimantan, which obtained an accuracy value of 45.25 for the carbon stock estimation model for all species and 31.82 for the dominant species. This research can strengthen the statement that the use of the NDVI vegetation index is a reference for estimating mangrove carbon stocks.

Mangrove carbon stocks in eastern Maumere Bay

The distribution map of surface carbon values in eastern Maumere Bay is presented in Figure 8 (a, b, c). Eastern Maumere Bay, which includes the islands of Kojadoi, Talibura, Darat Pantai, and Nangahale, has 527.93 ha of aboveground mangrove stands. The biomass carbon stock in these stands is 29,760.52 tons C, or an average of 56.34 tons C/ha. The second factor influencing the decline in mangrove cover in Maumere Bay is the natural environment. According to Gumilang *et al.* (2013), the 1992 tsunami caused a significant reduction in the area of mangrove habitat in Maumere Bay based on Landsat satellite imagery. According to Vincentius *et al.* (2018), the earthquake caused part of the land to sink up to 20 m from the mainland.

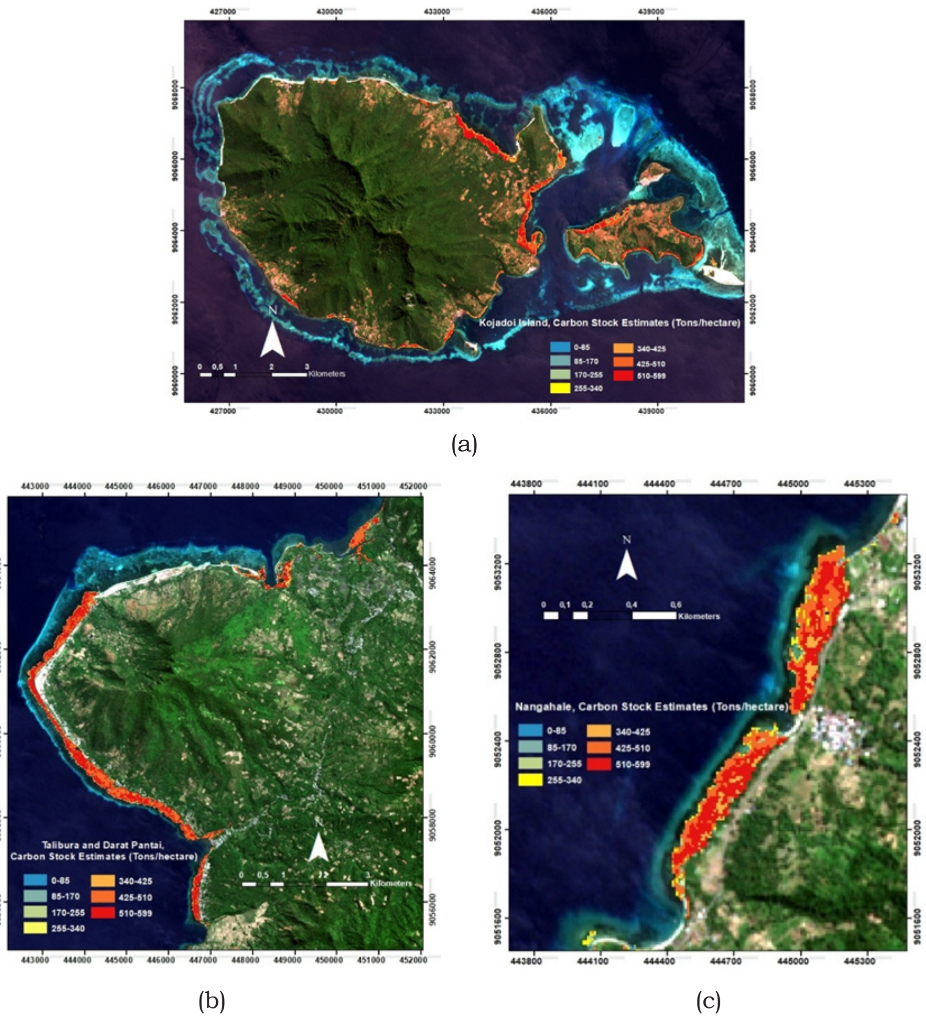

Figure 8. Map of estimated carbon stocks in eastern Maumere Bay: (a) Kojadoi Island, (b) Talibura and Darat Pantai, and (c) Nangahale.

The carbon in mangrove roots (belowground biomass) is not included in the surface carbon value of mangrove stands (aboveground biomass). Tree diameter impacts mangrove biomass values in addition to species density. Biomass and tree dimensions (diameter and height) are closely related, particularly for tree diameter. Increasing tree diameter results in a proportional increase in the biomass of each component (Haryati *et al.* 2024).

Compared with the results of research conducted by Kusuma *et al.* (2023) in Sungai Nibung Village, Tulang Bawang Regency, Lampung Province, which revealed that the average carbon value of mangrove stands ranged from 24.9 tons C/ha to 597.5 tons C/ha, the carbon value of stands in eastern Maumere Bay, at 56.34 tons C/ha, It can be said that the range is still lower. This is influenced by the smaller diameter of mangrove trees in eastern Maumere Bay compared to Sungai Nibung Village, Tulang Bawang Regency, Lampung Province. The amount of carbon stored in tree stands increases with increasing tree diameter.

CONCLUSION

Aboveground carbon biomass stocks in mangrove stands in the eastern part of Maumere Bay, which includes Kojadoi Island, Talibura, Darat Pantai, and Nangahale, were estimated using Sentinel-2A satellite imagery. A regression algorithm using the NDVI vegetation index and actual carbon stock data was used to obtain carbon stock values. Actual carbon stock values were obtained using aboveground biomass or an allometric formula. Sample points were selected using a stratified sampling technique. Total carbon stocks were estimated using the exponential regression equation $y = 13.637e^{2.0499x}$, where x is the NDVI extraction value and y is the carbon stock, with a coefficient of determination (R^2) of 0.8373. The eastern part of Maumere Bay has an average of 56.34 tons of C/ha, with a total aboveground carbon stock of 29,760.52 tons and a mangrove cover area of 527.93 ha.

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