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Carbon stock estimation of mangrove vegetation using remote sensing in Bacan, Awanggoa District, South Halmahera

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ABSTRACT

Awanggoa Village in Bacan District, South Halmahera Regency, has experienced significant residential expansion, converting around 9 hectares of mangrove land into a residential area. The remaining mangrove ecosystem, covering an area of 16.84 hectares in the northern part of the village, is starting to experience degradation, especially along the coast and southern areas. This condition requires management policies that ensure the sustainability of the ecosystem. The purpose of this research is to analyze the NDVI condition of the mangrove ecosystem, as well as measure biomass, carbon stock, and CO₂ absorption, using remote sensing methods via the GEE application (<https://code.earthengine.google.com>) with data collected from January 1 to December 31, 2023. The research results show a total biomass of 101.21 tons ha⁻¹, carbon stock of 47.57 tons C ha⁻¹, and CO₂ storage of 174.88 tons C. Dense vegetation is very important for carbon storage and emission reduction, thus supporting sustainable mangrove ecosystem management and environmental conservation efforts.

Introduction

The identified mangrove species are commonly found along the coastlines of Indonesia and North Maluku, particularly in South Halmahera District. The mangrove types discovered include *Rhizophora apiculata* and *Rhizophora mucronata*, which belong to the Rhizophoraceae family, while *Sonneratia alba* serves as the representative species of the Sonneratiaceae family. Rhizophoraceae contains a greater diversity of species compared to Sonneratiaceae. These species are capable of thriving in a variety of environments (Najamuddin *et al.*, 2024).

Many studies on vegetation conditions use remote sensing systems to estimate carbon stocks in mangrove forest areas in Indonesia. In addition to being able to assess various vegetation conditions Normalized Difference Vegetation Index (NDVI), satellites can also detect ecosystem productivity, such as Fraction of Photosynthetically Active Radiation (FPAR), Gross Primary Productivity (GPP), Net

Primary Production (NPP), and Leaf Area Index (LAI), as well as other parameters. In addition, satellites can also be used to estimate biomass, carbon stocks, and stored CO₂ absorption (Adni *et al.*, 2024; Arfan *et al.*, 2024; Febrianto *et al.*, 2022; Hati *et al.*, 2024; Julzarika *et al.*, 2024; Nursaputra *et al.*, 2024; Paramanik *et al.*, 2024).

Mangrove forests play a crucial role in sequestering atmospheric CO₂, as highlighted in this literature review on the impacts of anthropogenic activities on these vital ecosystems. Analyzing fifty-three research papers published from 1975 to 2024, the study underscores how human activities, such as land conversion, mining, and pollution, threaten mangroves, reducing forest areas and altering species composition. Despite these challenges, mangroves are essential for carbon absorption, mitigating climate change effects and supporting coastal ecosystems. The review emphasizes the need for further research, particularly in neotropical countries, to better understand and address the anthropogenic

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threats to mangrove forests and enhance their conservation and sustainable management strategies (Bhagarathi & DaSilva, 2024).

In Indonesia, *Rhizophora mucronata* emerges as the most effective species for carbon sequestration, capable of absorbing 43,130.21 kg C ha⁻¹. This is followed by *Bruguiera gymnorhiza*, *Sonneratia alba*, and *Avicennia alba*. The findings underscore the critical role of mangroves in mitigating atmospheric CO₂ levels, emphasizing their importance in climate change mitigation efforts (Adame *et al.*, 2024; Isnani & Masjud, 2024).

Materials and Methods

Location and time of research

This research is located at the Ake Awanggoa River Estuary, South Halmahera Regency, North Maluku, as shown in Figure 1. Geographically, the Ake Awanggoa Estuary is located at -0.624822" S to -0.619523 "S and 127.458881" E to 127.459407" E. The Ake Awanggoa River Estuary has an area of 16.84 ha, and the land is used as a household fuel.

The data used in this study is Sentinel-2 ('COPERNICUS/S2_SR'), acquired from January 1, 2023, to December 31, 2023, and the path to adding image collections for Copernicus S2 surface reflectance via the Google Earth Engine site <https://code.earthengine.google.com>.

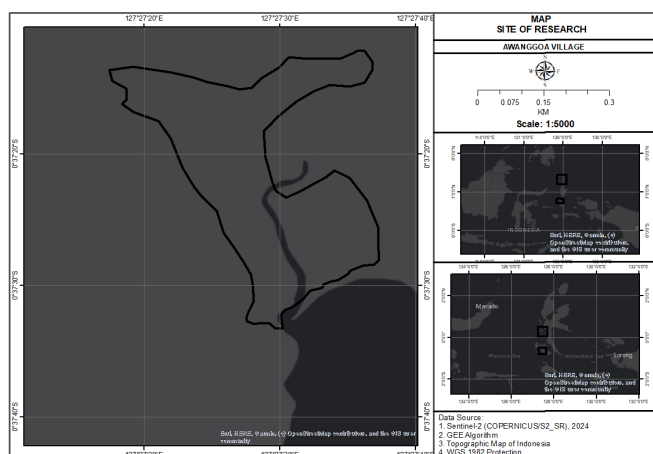


Figure 1. Map of site research at the Ake Awanggoa River estuary, Bacan District, South Halmahera Regency, North Molluca, Indonesia

Atmospheric Correction

Atmospheric correction of COPERNICUS/S2_SR imagery reduces the influence of the atmosphere on satellite imagery data. This process eliminates the effects of light scattering and absorption by particles in the atmosphere, such as aerosols, water vapour, and gases. In Google Earth Engine, atmospheric correction is performed

automatically using the bottom-of-atmosphere (BOA) method, where reflectance values at the earth's surface are calculated. The results of this correction ensure that the resulting imagery data more accurately represents the actual surface conditions.

Radiometric Correction

Radiometric correction of COPERNICUS/S2_SR images aims to adjust pixel values to conform to certain standards that allow comparison between images at different times. This process eliminates variations caused by sensor conditions, such as camera sensitivity or changes in observation angle. In Google Earth Engine, radiometric correction is performed automatically to produce homogeneous data, where reflectance values from objects on the earth's surface are normalised according to the Sentinel-2 satellite observation standards.

Data analysis

Vegetation Index

NDVI data analysis on Google Earth Engine is done automatically through the editor code. The first stage begins by loading a collection of Sentinel-2 satellite images, which are filtered based on a specific region and time. The required bands, NIR (B8) and Red (B4), are then selected. NDVI calculations are performed using the formula $(\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red})$, where NIR and Red are each taken from the appropriate band. The NDVI results can then be visualised with certain parameters, such as a range of values between -1 and 1, to indicate the level of vegetation in the observed area.

NDVI Classification and Analysis in ArcGIS Through Reclassify

The export of NDVI imagery as Image.tif to Google Drive is done to continue the classification process in ArcGIS. After the image is imported into ArcGIS, the NDVI value is reclassified using the Reclassify function to divide the range of NDVI values into several classes according to the level of vegetation (Febrianto *et al.*, 2022). This process groups areas based on low to high vegetation categories. After reclassification, statistical analysis is continued to calculate the average NDVI value in each resulting class so that information on the distribution and level of vegetation in the analysed area can be obtained in detail.

Above Ground Biomass (AGB) estimation

Estimation of aboveground biomass values was carried out using the NDVI results approach correlated with Above Ground Biomass (AGB) in mangroves, which has a correlation value of 0.787 according to research by Hastusi et al. (2018) as follows:

$$ABG = 305.9 * NDVI^{4.864} \dots \dots \dots 1$$

NDVI is the Vegetation Index value, while AGB is the Above Ground Biomass value (ton ha⁻¹).

Below Ground Biomass (BGB) estimation

The estimated value for Belowground Biomass (BGB) was obtained from the AGB estimate formulated based on the equation prepared by Cairns et al. (1997) as follows:

$$BGB = \exp(-1.0587 + 0.8836 * \ln(AGB)) \dots 2$$

AGB is the value of Above Ground Biomass (ton ha⁻¹), while BGB is the value of Below Ground Biomass (ton ha⁻¹).

Total Accumulated Biomass (TAB) Calculation

Total Biomass Accumulation (TAB) is formulated using:

$$TAB = ABG + BGB \dots \dots \dots 3$$

TAB = Total Accumulated Biomass (ton ha⁻¹).

Total Carbon Stock (TCS) calculation

Calculation of total carbon stock based on Westlake (1963) using the following formula:

$$TCS = TAB * \% C \text{ organic} \dots \dots \dots 4$$

TCS = the value of Total Carbon Stock (ton C ha-1), TAB = the value of Total Accumulated Biomass (ton ha-1), %C organic = the percentage value of carbon stock (0.47) or using the value of carbon emitted from the measurement results in the laboratory.

Amount of CO₂ Sequestration (ACS) calculation

IPCC (2001) suggests converting carbon stock from biomass to carbon dioxide uptake using the following conversion:

$$ACS = 3.67 * TCS \dots \dots \dots 5$$

ACS = the Amount of CO₂ Sequestration (ton C ha-1), TCS = the value of Total Carbon Stock (ton C ha-1).

Results

Condition of Normalized Difference Vegetation Index

The NDVI content in the Awanggoa River estuary ranges from 0.058 to 0.650, with an average value of 0.505. This indicates that the mangrove vegetation in the area varies from unhealthy to very healthy, but overall, the vegetation condition tends to be healthy. An average value approaching 0.505 indicates that most areas have fairly good vegetation.

Table 1. Distribution of Mangrove NDVI Cover Classes in the Area Around Ake Awanggoa Estuary

NDVI Coverage	Category	Area (ha)	% Area
High	0.5641-0.602	7.52	44.66%
Moderate	0.3510-0.546	5.94	35.27%
Low	0.2510-0.351	2.2	13.06%
Very Low	0.051-0.2510	1.18	7.01%
Total	0.051-0,602	16.84	100%

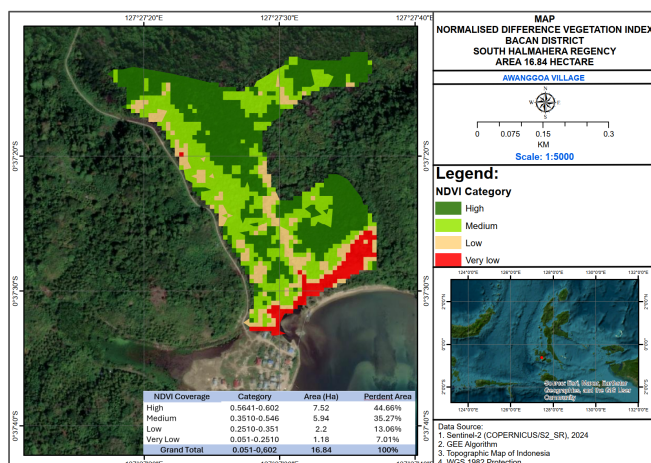


Figure 2. Distribution Map of Mangrove NDVI Cover Class in the Area Around Ake Awanggoa Estuary

Above Ground Biomass (AGB)

Data analysis shows (Table 2) that of the total area of 16.84 hectares, the category with the highest NDVI value covers the largest area, which is 7.52 hectares (44.66% of the total), with an above ground biomass (AGB) of 69.42 tons ha⁻¹. The moderate NDVI category covers 5.94 hectares (35.27%), with an AGB of 18.12 tons ha⁻¹. Meanwhile, the low NDVI category covers 2.2 hectares (13.06%) with an AGB of 4.55 tons ha⁻¹. Finally, the category with very low NDVI has the smallest area, 1.18 hectares (7.01%) without AGB. The total AGB for all categories is 92.09 tons, with a range of NDVI values between 0.051 and 0.602.

Table 2. Above Ground Biomass (AGB) in the mangrove ecosystem at the Ake Awanggoa River Estuary

NDVI Coverage	Area (ha)	AGB (ton ha ⁻¹)
High	7.52	69.42
Moderate	5.94	18.12
Low	2.20	4.55
Very Low	1.18	-0.00
Total	16.84	92.09

Below Ground Biomass (BGB)

Based on the analysis results [Table 3](#), the total area studied was 16.84 hectares with varying NDVI categories. The highest NDVI category covers an area of 7.52 hectares with an underground biomass (BGB) of 5.63 tons ha⁻¹. The moderate NDVI category covers 5.94 hectares with a BGB of 3.81 tons ha⁻¹. The low NDVI category covers 2.20 hectares with a BGB of 1.32 tons per hectare. Meanwhile, the very low NDVI category covers the smallest area of 1.18 hectares and shows a negative BGB value of -1.64 tons ha⁻¹. The total BGB of all categories is 9.12 tons.

Table 3. Below Ground Biomass (BGB) in the mangrove ecosystem at the Ake Awanggoa River Estuary

NDVI Coverage	Area (ha)	BGB (ton ha ⁻¹)
High	7.52	5.63
Moderate	5.94	3.81
Low	2.20	1.32
Very Low	1.18	- 1.64
Total	16.84	9.12

Total Accumulated Biomass (TAB)

Based on the results in [Table 4](#), the total area analyzed was 16.84 hectares, with variations in NDVI levels. The category with the highest NDVI covers an area of 7.52 hectares, with a total aboveground biomass (ABT) of 75.05 tons per hectare. The moderate NDVI category covers an area of 5.94 hectares with a TAB of 21.93 tons per hectare. The area covered for the low NDVI category is 2.20 hectares with a TAB of 5.87 tons per hectare. Meanwhile, the category with very low NDVI covers the smallest area, 1.18 hectares, with a negative TAB of -1.64 tons per hectare. The total TAB for all categories is 101.21 tons.

Table 4. Total Accumulated Biomass (TAB) in the mangrove ecosystem at the Ake Awanggoa River Estuary

NDVI Coverage	Area (ha)	TAB (ton ha ⁻¹)
High	7.52	75.05
Moderate	5.94	21.93
Low	2.20	5.87
Very Low	1.18	-1.64
Total	16.84	101.21

Total Carbon Stock (TCS)

Based on the analysis results in [Table 5](#), the total area studied was 16.84 hectares, with the distribution of total carbon storage (TSC) varying based on the NDVI category. In the highest NDVI category, the area reached 7.52 hectares with a TSC of 35.27 tons of C ha⁻¹. The medium NDVI category covers an area of 5.94 hectares with a TSC of 10.31 tons of C ha⁻¹. The low NDVI category covers 2.20 hectares with a TSC of 2.76 tons of C ha⁻¹. Meanwhile, the very low NDVI category covers the smallest area, 1.18 hectares, with a negative TSC value of -0.77 tons of C ha⁻¹. The total carbon storage from all categories is 47.57 tons.

Table 5. Total Carbon Stock (TCS) in the mangrove ecosystem at the Ake Awanggoa River Estuary

NDVI Coverage	Area (ha)	TSC (ton C ha ⁻¹)
High	7.52	35.27
Moderate	5.94	10.31
Low	2.20	2.76
Very Low	1.18	- 0.77
Total	16.84	47.57

Amount of CO₂ Sequestration (ACS)

Based on the analysis results of [Table 6](#), the relationship between NDVI coverage and carbon storage in an area of 16.84 hectares can be seen. The area with high NDVI coverage (7.52 hectares) contributed the largest carbon storage, 129.45 tons, while medium coverage (5.94 hectares) stored 37.82 tons of carbon. For low coverage (2.20 hectares), carbon storage reached 10.13 tons; in the area with very low coverage (1.18 hectares), there was a carbon release of -2.82 tons. In total, this area stores 174.58 tons of carbon, with a trend showing that the higher the vegetation coverage, the greater the carbon storage.

Table 6. Amount of CO₂ Sequestration (ACS) in the mangrove ecosystem at the Ake Awanggoa River Estuary

NDVI Coverage	Area (ha)	CO ₂ (ton C ha ⁻¹)
High	7.52	129.45
Moderate	5.94	37.82
Low	2.20	10.13
Very Low	1.18	- 2.82
Total	16.84	174.58

Discussion

Normalized Difference Vegetation Index (NDVI) analysis has become an important tool in estimating Above Ground Biomass (AGB) in various ecosystems, including mangrove and subtropical forests. NDVI, which measures the greenness of vegetation, has a significant correlation with AGB due to its ability to capture variations in vegetation density and health. Studies have shown that NDVI can provide accurate estimates of aboveground biomass, with linear regression models showing a strong correlation between NDVI and AGB, as seen in previous studies (Hastuti *et al.*, 2018; Wahlang & Chaturvedi, 2020). This approach not only helps in biomass mapping but also sustainable natural resource management, especially in the context of climate change and ecosystem conservation.

Normalized Difference Vegetation Index (NDVI) analysis has become an important tool in estimating Above Ground Biomass (AGB) in various ecosystems, including mangrove and subtropical forests. NDVI, which measures the greenness of vegetation, has a significant correlation with AGB due to its ability to capture variations in vegetation density and health. Studies have shown that NDVI can provide accurate estimates of aboveground biomass, with linear regression models showing a strong correlation between NDVI and AGB, as seen in previous studies (Hastuti *et al.*, 2018; Wahlang & Chaturvedi, 2020). This approach not only helps in biomass mapping but also sustainable natural resource management, especially in the context of climate change and ecosystem conservation.

Underground biomass plays an important role in carbon storage in mangrove ecosystems, so it needs to be calculated appropriately. Errors in estimating this biomass can lead to a lack of recognition of mangroves' contribution to climate change mitigation and forest management, which has the potential to influence overall conservation policy (Henri *et al.*, 2024; Njana, 2024).

The low underground biomass in the mangrove ecosystem is caused by some of it being carried away

by currents when the water recedes, while the other part remains as soil carbon in the ecosystem. Species characteristics and environmental conditions play a role in influencing productivity and biomass distribution, which reflects carbon dynamics in mangrove ecosystems. This understanding can support climate change mitigation efforts through sustainable natural resource management (Ávila-Acosta *et al.*, 2024).

Mangroves are very efficient natural carbon stores, storing carbon both in above- and below-ground biomass and in carbon-rich soil. Mangroves are capable of storing 3-5 times more carbon than land forests, but changes in land use, such as conversion to agricultural land, deforestation, and pollution, can reduce mangroves' capacity to store carbon and have the potential to release carbon emissions into the atmosphere. Mangrove carbon stocks, especially underground, often dominate total carbon storage, with variations depending on species and location (Ouyang *et al.*, 2024). Plant residues and microbes play an important role in increasing organic carbon in the soil, with leaves, roots, and microbial products contributing directly to carbon accumulation, strengthening the function of mangroves as efficient carbon stores. For optimal blue carbon management strategies, a deeper understanding of the role of these residues is needed, as carbon contributions vary depending on environmental factors such as salinity, soil depth, and mangrove species. These findings guide policymakers and scientists in formulating more effective conservation strategies (Qin *et al.*, 2024).

Overall, NDVI monitoring in the Awanggoa River estuary provides an important picture of the condition and health of mangrove vegetation in the area. Understanding the various environmental factors and human activities that affect NDVI values allows for appropriate conservation measures to protect and restore the mangrove ecosystem. This effort is crucial in maintaining biodiversity and supporting the sustainability of natural resources that depend on coastal ecosystems. With a holistic and sustainable approach, it is hoped that the increase in NDVI values can reflect improvements in vegetation conditions in the area.

Warming of 4°C significantly increases the rate of carbon sequestration in mangroves. Increasing temperatures can stimulate photosynthesis and vegetation growth, increasing carbon accumulation above and below ground (Qiao *et al.*, 2024). Mangroves are efficient carbon stores, storing carbon in biomass above and below ground and carbon-rich soil. They contribute greatly to the global carbon

cycle and climate change mitigation. However, mangroves face serious threats, such as deforestation, land conversion, and climate change, with more than 35% of mangrove areas lost since the 1980s, endangering their ecological function and absorption capacity. This study highlights advances in remote monitoring techniques that enable more accurate mapping and assessment of carbon stocks and mangrove ecosystem dynamics. It is estimated that mangroves globally store around 4.19 Pg of carbon, with 2.96 Pg stored in soil and 1.23 Pg in biomass. Countries such as Indonesia, Brazil, Malaysia, and Papua New Guinea contribute over 50% of this carbon stock. Mangrove deforestation reduces carbon storage capacity and increases global greenhouse gas emissions. Every 4 GtC released into the atmosphere can increase CO₂ concentrations by one ppm, showing the importance of conserving mangroves to mitigate climate change (Choudhary et al., 2024).

Since 2022, the mangrove forest area at the Ake Awanggoa River Estuary that releases carbon or CO₂ emissions, especially those in the very low NDVI category, has been rehabilitated to restore ecological and socio-economic functions and mitigate global warming. This rehabilitation program is the result of collaboration between PT. Tremegah Bangun Persada and the Faculty of Fisheries and Marine Sciences, Khairun University, aim to improve environmental quality and support the area's sustainability, as seen in Figure 3.



Figure 3. Mangrove Rehabilitation Process at the Awanggoa River Estuary with the community

Conclusion

The study results show that the mangrove ecosystem at the mouth of the Ake Awanggoa River, South Halmahera Regency, has great potential for storing carbon through above-ground and underground biomass. With a total biomass of 101.21 tonnes ha⁻¹ and a carbon stock of 47.57 tonnes C ha⁻¹, this mangrove forest can absorb up to 174.58 tonnes of CO₂. Factors such as vegetation health, measured through NDVI, greatly influence these ecosystems' ability to store carbon. However,

degradation due to human activities, such as land conversion and deforestation, threatens the sustainability of mangroves and their capacity as carbon sinks. Therefore, sustainable management policies are needed to protect and restore mangrove ecosystems to support climate change mitigation and environmental conservation.

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