Vol. 5, No. 6, June 2024
E-ISSN: 2723-6692
P-ISSN: 2723-6595
http://jiss.publikasiindonesia.id/

Utilisation of Sentinel-2A Imagery for Estimation of Mangrove Carbon Stock in Mamminasata Area, South Sulawesi

Munajat Nursaputra, Kurniawan, Daud Malamassam
Universitas Hasanuddin Makassar, Indonesia
Email: munajatnursaputra@unhas.ac.id
Correspondence: munajatnursaputra@unhas.ac.id*

KEYWORDS
Carbon Reserves; NDVI; Citra Sentinel-2A; Mangrove Forest; Mamminasata

ABSTRACT
Population growth and land conversion have led to the degradation of mangrove forests on the southern coast of South Sulawesi, especially the Mamminasata area. Reduced mangroves increase carbon dioxide in the atmosphere. However, data on the potential carbon absorption of mangroves is still lacking. To overcome this, remote sensing is used to estimate carbon reserves. This reseach utilises Sentinel-2A imagery to estimate mangrove carbon stocks in Mamminasata. The image processing process includes radiometric correction, atmospheric correction, image classification, and extraction of NDVI values. The NDVI value is used to classify the density of mangroves into sparse, medium, and dense, covering 1,244.75 hectares. Field data collection was carried out through a survey of forest stand measurements. The results of NDVI transformation show a value range of 0.2 to 0.8 for mangrove objects in the Mamminasata area. The NDVI data on the analysed images were then made into three density classes. The rare density class has a carbon value of 3.56 – 21.16 Ton C/ha, the medium density class is between 21.17 – 31.49 Ton C/ha, and the dense density class is between 31.50 – 39.18 Ton C/ha. Regression analysis shows a strong correlation between NDVI and carbon stock (R^2 = 0.7134). This study confirms the effectiveness of remote sensing in environmental monitoring and mangrove conservation. These findings support conservation efforts and sustainable management policies by highlighting areas with high carbon sequestration potential.

1. Introduction

Mangrove forests in Indonesia great importance, with the most extensive distribution in the world. According to data from the National Institute of Aeronautics and Space (LAPAN) in 2016, mangrove forests in Indonesia cover about 2,408,652.39 hectares, highlighting their critical ecological value for the country. These mangroves play an important role in coastal protection, biodiversity, and carbon sequestration, which is essential for climate change mitigation and supporting sustainable ecosystems (A. Malik et al., 2016; Mukrimin et al., 2021). South Sulawesi is one of Indonesia's provinces with a large mangrove ecosystem, with an area of about 9,335.18 hectares. This mangrove area is spread along the west, south, and east coasts of the province. However, population growth and land conversion are significant threats to the sustainability of these mangrove forests. In particular, the southern coast of South Sulawesi, including the

Mamminasata metropolitan area (consisting of Makassar City, Maros Regency, Gowa Regency, and Takalar Regency), faces a critical challenge from mangrove degradation (Indrayani et al., 2021; Siddiq et al., 2020).

This forest degradation can adversely affect natural protection mechanisms and increase the vulnerability of these areas to environmental and climate change. Data from LAPAN shows that between 2016 and 2017, the area of mangrove forests on the southern coast of South Sulawesi decreased by 119.67 hectares, from 874.58 hectares to 754.91 hectares. This alarming trend highlights the urgent need for more intensive conservation efforts (Hu et al., 2020). Mangrove forests are known to have a high carbon storage capacity, able to store up to four times more carbon than other tropical forests. This makes its conservation important for global climate change mitigation efforts. While important, data on the carbon sequestration potential of mangrove forests is still limited, posing challenges to effective conservation and management strategies. Therefore, efficient methods for estimating and monitoring carbon stocks in mangrove forests are essential for sustainable ecosystem management and policy formulation (Pham et al., 2019).

Remote sensing has emerged as an effective technique for estimating carbon stocks, offering a cost-effective and accurate method for monitoring ecosystems at scale. The Sentinel-2A satellite, equipped with multispectral sensors, has been used to detect and analyse the condition of mangrove forests more precisely and efficiently. Recent studies have demonstrated the usefulness of Sentinel-2A imagery in mapping mangrove distributions and estimating carbon stocks, demonstrating its potential in environmental monitoring (Sugara et al., 2022; Wang et al., 2018). The studies highlight the effectiveness of remote sensing in providing detailed and accurate data on mangrove ecosystems, which is critical for conservation efforts (Putra et al., 2022; Rahmadi et al., 2021). While promising advances in remote sensing applications for mangrove monitoring, there are still significant gaps in the precise estimation of carbon stocks in various mangrove ecosystems. Research in Labuan Tereng, West Lombok Regency, using Sentinel-2A imagery, found that *R. mucronata* dominated the area with an average carbon reserve of 122.1 tons per hectare, with a total of 1,359.9 tons of carbon for the area. However, variations in the composition of local mangrove species and their carbon storage capacity require further region-specific studies to ensure accuracy (Hambali et al., 2023).

Research on the south coast of Sampang Regency using a hybrid model for carbon estimation revealed that the total carbon stock of mangroves is 350,721.7 tons, with an average of 300.3 tons per hectare. These findings highlight the need for a tailored remote sensing methodology to address the diverse characteristics of mangrove forests in different regions. In addition, integrating various remote sensing data sources can improve the accuracy of carbon stock estimates, but it is still underexplored in many areas (Muhsoni, 2018). In addition, although the Sentinel-2 sensor has been validated for its usefulness in mapping mangrove areas and species, more comprehensive studies that integrate multispectral data with field measurement efforts are needed. This integration will help refine the estimation models and ensure they are robust and applicable in a variety of ecological environments. The limited availability of such integrative studies highlights the critical research gaps seeks to address (Wang et al., 2018).

This study aims to estimate carbon stocks in mangrove forests throughout the Mamminasata region, including Makassar City, Maros Regency, Gowa Regency, and Takalar Regency. The study leverages the advanced capabilities of the Sentinel-2A satellite to provide accurate and up-to-date data on mangrove carbon reserves, which are essential for effective conservation and management strategies. The application of Sentinel-2A multispectral imagery in the specific context of the Mamminasata region is a novelty that has not been studied before. By integrating remote sensing data with field measurements, this research will contribute to understanding the carbon sequestration potential of mangrove forests in South Sulawesi and provide a scientific basis for informed conservation policies and practices. In addition, the methodology used in this study can be developed to estimate carbon stocks in other mangrove ecosystems that face similar environmental threats.

2. Materials and Methods

Location and Time of Research

This research was carried out for 8 months, starting from March 2021 to November 2021. The research is divided into two main stages, namely field activities and data analysis. Field activities were carried out in the Mamminasata area, which covers the areas of Makassar City, Maros Regency, Gowa Regency and Takalar Regency, as shown in **Error! Reference source not found.**. The data analysis stage was carried out at the Forestry Planning and Information Systems Laboratory, Hasanuddin University.

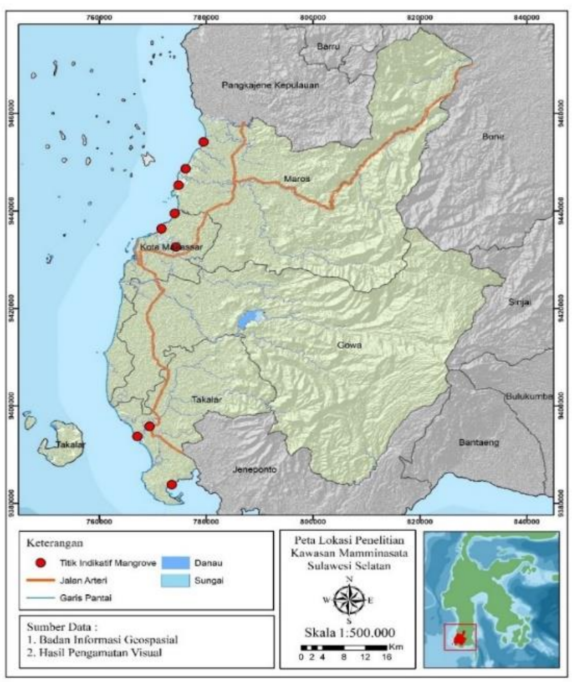

Figure 1 Map of the Research Location

Research Tools and Materials

The tools used for field data collection include the Global Positioning System (GPS) to determine location coordinates, measuring tapes and rollmeters for plotting and measuring the diameter of the stands, as well as neat ropes and tally sheets to record data in the field. In addition, ArcGIS software is used for data processing and spatial analysis and mapping. The main material used in this study is the Sentinel-2A Level L1C Image Recorded in 2020.

Field Data Collection

Field data collection was carried out through measurements of mangrove forest stands on a predetermined sample plot. The location of the sample plot was selected using the stratified sampling method based on the density of mangroves obtained from the results of satellite image processing. A sample plot measuring 10 m x 10 m was used to record vegetation at the tree level (BSN, 2011). The stand variables measured in the field include the type of tree and the diameter of the tree at chest height (DBH). The number of sample plots is determined using the Slovin formula (Sevilla, 2007), taking into account the population area and fault tolerance limits.

Data Analysis

1. Interpretation of Mangrove Distribution and Density

Sentinel-2A image processing includes radiometric correction, atmospheric correction, image classification, and extraction of vegetation index values using *the Normalized Difference Vegetation Index* (NDVI). Radiometric correction is performed to correct pixel values due to atmospheric disturbances, which are a major source of errors in satellite image processing (Kamal et al., 2020; Wu et al., 2018). This process uses a radiometric calibration tool to eliminate distortions caused by the position of the sun. Atmospheric correction is performed using a flash atmospheric correction tool to eliminate distortions that affect the reflectance value in the image (Belov & Myasnikov, 2016; Cetin et al., 2017).

After corrections, the next classification of mangrove vegetation was carried out. To clarify the object to be classified, a combination of bands 4 (red), 3 (green), and 2 (blue) is used. These bands were chosen because they have high sensitivity and high reflectance value to vegetation, making it easier to identify mangrove cover (Ghorbanian et al., 2021; Purwanto & Asriningrum, 2019). After that, image sharpening is carried out to help visually interpret the mangrove cover (Ulfarsson et al., 2019). This identification involves the ability to interpret images through elements such as colour, texture, size, shape, pattern, shadow, and association to recognise objects. The estimation of above-surface biomass using the Sentinel-2A image will be based on the value of the NDVI vegetation index and the results of biomass measurements in the field. NDVI values were obtained through the transformation of the vegetation index which was regressed to the actual biomass values from the field. The calculation of the vegetation index using NDVI involves the red band and the near infrared band reflected by the vegetation. On Sentinel-2A satellite imagery, NDVI is calculated using bands 8 (near-infrared) and 4 (red) (Muhsoni et al., 2018; Rakuasa & Sihasale, 2023).

2. Estimated Carbon Stocks

The value of carbon reserves is obtained from the conversion of the value of the stand biomass. Information on mangrove biomass content was obtained using an allometric formula approach. This formula, which takes into account factors such as the diameter of the tree, the density of the wood, and the height of the tree, is essential for accurate calculations (Adame et al., 2017; Fatoyinbo et al., 2018; A. Malik et al., 2016; Sitoe et al., 2014; Trissanti et al., 2022). The allometric equations for several types of mangroves found in the Mamminasata Area are presented in **Error! Reference source not found.**.

Table 1 Allometric equations of several mangrove species

Spesies	Allometric equations	Source
Rhizophora apiculata	$B = 0{,}0275(DBH)^{3{,}22}$	(Amira, 2008; Pambudi, 2011)
Rhizophora mucronata	$B = 0{,}128(DBH)^{2{,}60}$	(Fromard et al., 1998)
Avicennia sp	$B = 0{,}0251\rho(DBH)^{2{,}46}$	(Komiyama et al., 2005)
Avicennia marina	$B = 0{,}1848\rho(DBH)^{2{,}3524}$	(Dharmawan & Siregar, 2008)

Where: B is Biomass (kg), = BJ Wood (g/cm3), DBH is Chest Height Tree Diameter (cm).

The distribution of biomass values obtained at the research site was then converted into the value of carbon reserves, which were multiplied by the value of the percentage of carbon content of 47% of the biomass. The creation of carbon stock maps is carried out based on the best models. The best model was obtained from the relationship between the content of biomass above the surface and the NDVI value of Citra Sentinel-2A, which was analysed using mathematical equations with linear, exponential and logistic models. The best model is depicted with a coefficient of determination (R2) value. This coefficient aims to measure how far the model can apply dependent variable variations, which are described as very low (0-0.19), low (0.2-0.39), medium (0.4-0.59), strong (0.6-0.79) and very strong (0.8-1.0) (Sugiyono, 2010). The carbon stock values were then distributed using a raster calculator in the ArcGIS Software spatial analyst *tool*. Then, the carbon reserve value in each mangrove density class is issued using zonal statistics as a table in the spatial analysis tool ArcGIS Software, where the data entered is the mangrove forest density raster data and the carbon stock raster data that was made previously.

3. Results and Discussions

Distribution and Density of Mangroves

The results of the interpretation show that the mangrove land cover in the Mamminasata area is found in Makassar City, Takalar Regency, and Maros Regency, covering an area of about 1,244.75 hectares, as depicted in **Error! Reference source not found.**. This interpretation shows a substantial distribution of mangrove forests in the three administrative regions. The validation process was carried out through field checks at 20 points, resulting in an *overall accuracy* of 90%. However, there are differences at two points, namely point 3 in Lakkang Village and point 19 in Maccini Baji Village, where the initial interpretation identifies these points as mangrove land cover, while the field check is a fish pond.

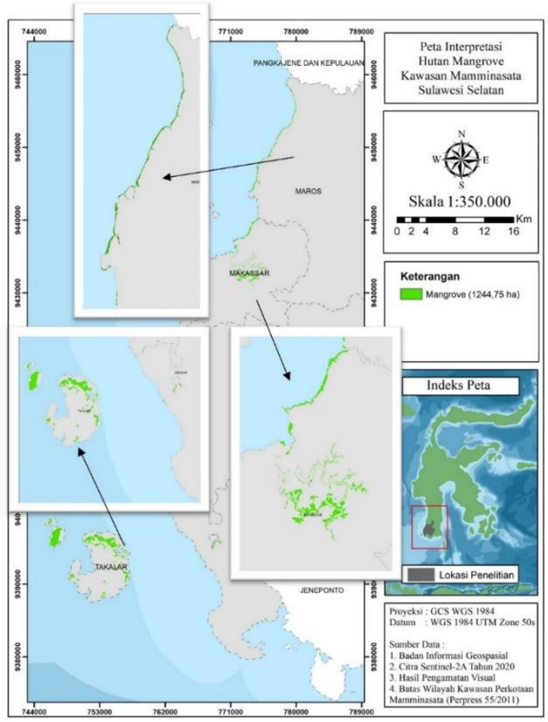

Figure 2 Interpretation Map of Mangrove Distribution in the Mamminasata Area

The findings of this study are in line with previous research that shows the effectiveness of Sentinel-2 imagery in mangrove forest mapping. For example, Hu et al. (2020) highlighted the significant improvement in spatial and temporal resolution offered by Sentinel-2 compared to Landsat imagery. Studies such as those conducted by Sugara et al. (2022) and Jia et al. (2019) telah berhasil menggunakan Sentinel-2 untuk mendeteksi mangrove yang terendam, mapping mangrove density, and estimating carbon stocks with reported accuracy exceeding 80%. Similarly, Aulia et al. (2022) recorded up to 86.07% accuracy for mangrove density mapping using Sentinel-2. The differences identified in Lakkang Village and Maccini Baji Village reflect the challenges noted by previous researchers in distinguishing mangrove land cover from other land uses such as fish ponds. This highlights the need to integrate multispectral data with field measurement efforts to improve the accuracy of mangrove mapping. Chen et al. (2022) and Maung (2023) It also emphasises the importance of combining remote sensing data with field validation to improve the accuracy of ecosystem assessments.

The identified mangrove areas in the study area were analysed to determine the level of mangrove density. Using the Normalization-Related Vegetation Index (NDVI), mangrove objects in the Mamminasata region show NDVI values ranging from 0.2 to 0.8. The NDVI data was then categorised into three density classes, namely -1 – 0.32 (rare), 0.33 – 0.42 (moderate), and 0.43 – 1 (dense) (Departemen Kehutanan, 2005), with the results presented in **Error! Reference source not found.** and **Error! Reference source not found.**. The total area for sparse density is 58.17 hectares, medium density covers 57.46 hectares, and dense density covers 1,129.12 hectares.

Table 2 Mangrove Forest Density in Mamminasata Area

Regency / City	District	Village	Area per Class Density (Ha)			Total (Ha)
			Infrequently	Medium	Heavy	
Makassar	Biring Kanaya	Untia	0,29	0,33	19,46	20,08
	Panakkukang	Pampang	2,00	1,72	58,85	62,57
		Panaikang	1,31	1,04	37,75	40,10
		Tello Baru	0,01	0,00	0,52	0,53
	Tallo	Lakkang	2,59	2,41	16,28	21,28
		Tallo	0,21	0,13	3,30	3,64
	Tamalanrea	Bira	0,13	0,19	15,11	15,43
		Kapasa	0,83	1,08	10,29	12,19
		Parang Loe	3,29	3,17	39,05	45,51
		Tamalanrea Indah	1,55	1,54	41,59	44,68
		Tamalanrea Jaya	0,00	0,01	0,00	0,01
Total Makassar			**12,21**	**11,62**	**242,20**	**266,02**
Maros	Bontoa	Ampekale	1,73	1,00	25,25	27,98
		Bonto Bahari	0,71	0,52	6,77	8,00
		Pajukukang	0,19	0,09	5,44	5,72
	Lau	Marrannu	0,69	0,73	24,52	25,94
	Maros Baru	Borimasunggu	1,03	1,16	29,28	31,47
	Marusu	Nisombalia	1,39	1,24	50,02	52,65
		Pabentengan	0,18	0,20	5,22	5,60
Total Maros			**5,92**	**4,94**	**146,50**	**157,36**
Takalar	Mangara Bombang	Banggae	0,09	0,09	2,94	3,12
		Laikang	0,45	0,31	3,46	4,22
		Panyangkalang	0,16	0,13	3,57	3,86
	Mappakasunggu	Maccinibaji	33,22	31,59	424,6	489,41
		Mattirobaji	5,41	8,23	285,84	299,48
		Takalar Kota	0,14	0,08	4,32	4,54
	Pattallassang	Pallantikang	0,17	0,2	8,07	8,44
	Polombangkeng Selatan	Pa'bundukang	0,4	0,28	7,62	8,29
Total Takalar			**40,04**	**40,91**	**740,42**	**821,36**
Total Mamminasata Area			**58,17**	**57,47**	**1.129,12**	**1.244,74**

The use of NDVI for mangrove density mapping is in line with various studies that have shown its effectiveness in estimating canopy cover, forest health, and mangrove structure (Lovelock et al., 2017; Pamungkas, 2023; Ticman et al., 2021). NDVI is widely recognized for its ability to monitor mangrove forest restoration, track changes in mangrove areas, and assess damage based on canopy density (Anggraini, 2023; Faizal et al., 2023). In addition, NDVI has been used to classify mangrove canopy density and estimate above-ground biomass within mangrove ecosystems, emphasising its flexibility and reliability in remote sensing analysis (Rinjani, 2024).

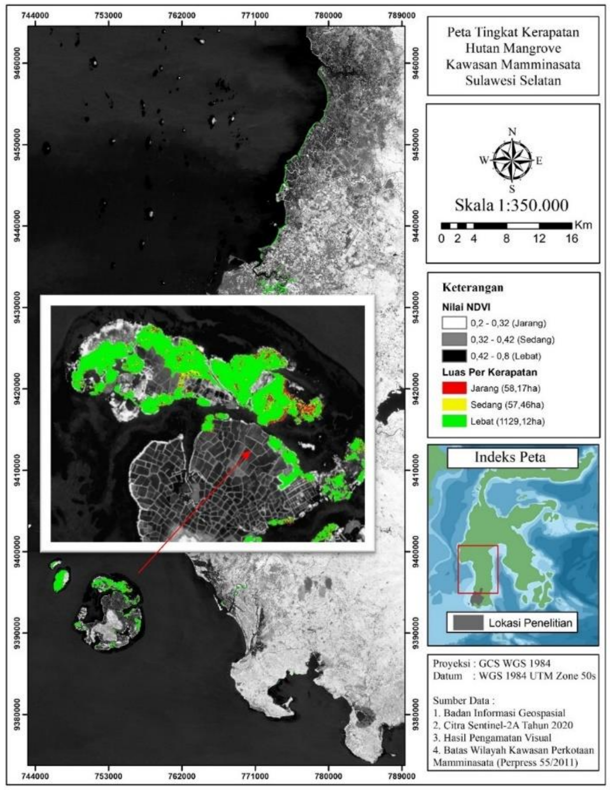

Figure 3 Map of Mangrove Density in Mamminasata Area

The findings in the Mamminasata region, which shows a dense density area of 1,129.12 hectares, are consistent with studies highlighting the extensive canopy cover of healthy mangrove ecosystems. Classification of mangrove densities into sparse, moderate, and dense categories facilitates targeted conservation efforts, as seen in other studies using NDVI to categorise canopy density levels and implement effective management practices (Singgalen et al., 2021). This density class is the basis for determining the number of sample plots for the calculation of carbon reserves in the field, where 2 plots for sparse density, 2 plots for medium density, and 39 plots for dense density are obtained. The application of Slovin's formula to determine the number of sample plots based on density class further strengthens the systematic approach used in this study to ensure accurate and representative sampling.

Estimated Carbon Stocks

The calculation of mangrove stand biomass in 43 sample plots in the Mamminasata area showed an average mangrove biomass of 689.20 kg/plot. The lowest biomass was recorded at 235.23 kg/plot in plot 21, which is categorised as sparse density, while the highest is 963.96 kg/plot, categorized as dense density. The biomass values obtained at the study site are then converted into carbon reserve information, which is usually expressed in carbon tons per hectare (tonC/ha). The average carbon reserve in the Mamminasata area was found to be 34.46 tonsC/ha. Furthermore, regression analysis was carried out to explore the relationship between NDVI values and carbon stocks, with the results of the regression analysis presented in

.

Table 3 Carbon Stock Estimation Model

Regresi	Model Persamaan	R2
Linear	y = 84,963x + 15,012	0,6733
Eksponensial	$y = 24{,}312e^{1.594x}$	0,6144
Logaritmik	y = 43,564ln(x) + 90,225	0,7134

The logarithmic regression model shows the highest coefficient of determination (R^2) of 0.7134, so it is selected as the best predictor model for estimating carbon stocks. It shows a strong relationship between carbon stock values and NDVI, where 71.34% of the variation in carbon stocks can be explained by NDVI values, with the remaining 28.66% due to other variables. These findings are consistent with previous studies that used regression models to analyse the relationship between NDVI and carbon stocks in various ecosystems. Malik et al., (2023) and Hidayah et al., (2022) has demonstrated the potential of NDVI as a predictor for carbon stock estimation, with the determination coefficient ranging from 0.7 to 0.98, highlighting the significance of NDVI in affecting above-ground biomass and carbon stocks.

The carbon stock in the study area is then calculated based on the density of mangrove forests to evaluate the potential carbon stocks in each vegetation density class. This was done to see the potential value of carbon stocks in each class of mangrove vegetation density. The carbon content is divided into three classes, namely sparse, medium and dense density classes. The distribution of carbon reserve values has been divided into three classes based on the classification of vegetation density. The rare density class has a carbon value of 3.56 – 21.16 Tons C/ha, the medium density class has a carbon value between 21.17 – 31.49 Tons C/ha, and the dense density class has a carbon value between 31.50 – 39.18 Tons C/ha. More details of carbon distribution in the Mamminasata area mangrove forest are presented in **Error! Reference source not found.**.

Table 4 Carbon Distribution of Mangrove Forests in the Mamminasata Area

No.	Density Type	comprehensive (ha)	Lowest Carbon Stocks (Ton C/ha)	Highest Carbon Reserves (Ton C/ha)
1	Infrequently	58,17	3,56	21,16
2	Medium	57,46	21,17	31,49
3	**Heavy**	1.129,12	31,5	39,18
	Total	**1.244,75**	**56,23**	**91,83**

The spatial distribution of mangrove carbon stocks using NDVI values as shown in **Error! Reference source not found.**, has actually been widely studied using remote sensing data and spatial modeling techniques to map and estimate carbon stocks in mangrove ecosystems. These studies highlight the spatial variability of carbon stocks in different areas of mangroves, providing essential insights into the distribution patterns and carbon sequestration potential of mangrove forests. For example, Pham et al., (2020) showed that the NDVI values obtained from satellite imagery effectively assessed changes in carbon stocks and identified areas with high carbon density.

The findings of this study, which classifies carbon stocks into sparse, medium, and dense classes, are in line with previous research that emphasized the usefulness of NDVI in determining vegetation density and appropriate carbon stocks (Aulia et al., 2022; I Gusti Agung Indah Mahasani et al., 2021; Sugara et al., 2022). The categorization of carbon stock values in the Mamminasata region into different density classes reflects the methodological approach used in similar studies, which further validates the effectiveness of NDVI in mangrove carbon stock assessments.

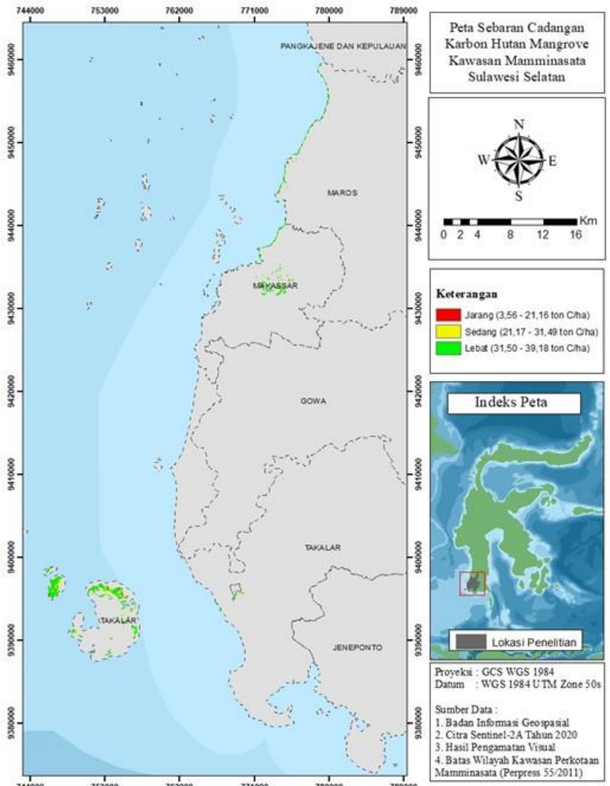

Figure 4 Map of the Distribution of Mangrove Forest Carbon Reserves in the Mamminasata Area

The findings of this study have significant implications for the conservation and management of mangrove ecosystems in the Mamminasata area. By accurately mapping the spatial distribution of carbon stocks based on vegetation density, this study provides important data for targeted conservation efforts. Identifying areas with high carbon density, which have greater carbon sequestration potential, is essential to prioritising conservation actions and mitigating the impacts of climate change. The integration of NDVI values in spatial analysis has proven to be very helpful in mapping and evaluating mangrove carbon stocks, contributing to a better understanding of the role of mangroves in carbon sequestration (Adni, 2024). The data generated from this study can inform conservation policy decisions and strategies, ensuring sustainable management of mangrove forests and their ecosystem services. Additionally, the study emphasises the importance of remote sensing technology in environmental monitoring, offering a reliable and efficient method for assessing ecosystem health and carbon stock dynamics over time.

4. Conclusion

This study successfully utilised Sentinel-2A imagery and NDVI values to estimate and map the carbon stock of mangrove forests in the Mamminasata area, South Sulawesi. The findings show that mangroves in the region cover an area of 1,244.75 hectares, with carbon stock values ranging from 3.56 to 39.18 Tons C/ha in various density classes. Logarithmic regression models show the highest accuracy in predicting carbon stocks, with an R^2 value of 0.7134, which shows a strong correlation between NDVI values and estimated carbon stocks. These results confirm the effectiveness of remote sensing technology, specifically the Sentinel-2A imagery, in providing accurate and reliable data for environmental monitoring. The study contributes to an increased understanding of the role of mangroves in carbon sequestration, emphasising its importance in climate change mitigation and ecosystem conservation. By identifying areas with high carbon sequestration potential, the study supports targeted conservation efforts and informs sustainable management practices. The integration of NDVI in spatial analysis offers a powerful method for assessing and monitoring mangrove ecosystems, providing valuable insights for policymakers and conservationists. Future research should focus on refining this methodology and expanding its application to other regions, ensuring a comprehensive and effective mangrove conservation strategy. The study highlights the critical role of mangroves in carbon storage and the importance of advanced remote sensing technology in environmental science.

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