Aboveground Biomass Estimation of Mangrove Ecosystem in the Anambas Islands Using Remote Sensing Data

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Abstract. The Anambas Islands is located in the Natuna Sea - the southern part of the South China Sea, encompassing vital marine ecosystems. Among these ecosystems, the mangrove stands out as crucial in the Anambas, playing an important role in providing a range of ecosystem services. However, spatial information regarding the condition of this ecosystem is very limited. In this study, our focus was on estimating and mapping the aboveground biomass (AGB) of mangroves across the Anambas using a combination of field survey and satellite remote sensing data. We employed seven vegetation indices along with five regression methods to determine the most suitable combination for producing an AGB. Our findings revealed that the incorporation of Sentinel-2 remote sensing images and field survey data can be used to model the AGB. The best combination model was the Modified Soil Adjusted Vegetation Index (MSAVI) and polynomial regression, achieving an accuracy of 72.09%. Anambas was estimated to possess a potential AGB of 369,371.47 tonnes and a carbon stock of 173,604.59 tonnes. These findings provide valuable information for regional conservation strategies, including the identification of protected zones, the establishment of a baseline for mangrove conditions, and the assessment of carbon credit in the Anambas.

1 Introduction

Mangrove is one of the Earth's most crucial marine ecosystems, offering an extensive array of services to our environment. They play a pivotal role in delivering a diverse set of benefits spanning ecological, social and economic benefits [1-2], including coastal protection from surges and waves, water filtration, a food source and nursery for fish and crustaceans, as well

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as a source of wood fuel, and opportunities for nature-based recreation [3-6]. Mangroves, being the only woody halophytes [7], have a crucial role in carbon storage within the context of climate change [8-9]. They are capable of storing organic carbon as sediment for extended periods and can also utilize carbon in the form of organic compounds [10-11].

Mangrove forests occur in tropical, subtropical, and temperate coastal tidal regions, often overlapping with significant anthropogenic pressures [12-13]. Currently, there is a disturbing decline in mangrove forest coverage due to insufficient management of land utilization, particularly in the agricultural, infrastructure, industrial, settlement, and tourism sectors [10]. In addition to the human factors, mangroves are also confronting natural threats from climate change, which are altering the frequency and intensity of weather cycles, impacting sea levels, wind patterns, and wave energy [12].

There is an urgent need for information concerning the current state of this vital ecosytem, given its role in long-term carbon sequestration and its significance in the context of global climate. Carbon stock information, which measures the quantity of organic carbon within a blue carbon ecosystem, is essential for attracting funds for the conservation and restoration of mangroves [14]. One of the carbon pools found in mangroves is the aboveground biomass (AGB), which comprises the living biomass above the ground, such as stems, branches, leaves, bark, and seeds [1].

Conducting a traditional field survey of mangrove biomass can be quite challenging due to the muddy soil environment, the substantial weight of the wood, and the need to employ destructive methods [7]. Consequently, in situ measurements through the allometric approach have become the predominant method for assessing mangrove biomass [11]. Nonetheless, this approach presents its own set of challenges, particularly in mangrove areas with exceptionally high density and limited accessibility [15]. Furthermore, when applied over large areas, it can be expensive and time-consuming [16].

Remote sensing technology has demonstrated its capability in surpassing the limitations of traditional surveys. This technique offers a cost-effective and time-efficient solution with the ability to rapidly map large and inaccessible areas [6, 16]. Moreover, it possesses the temporal capability to monitor changes over time [10]. The Anambas Islands, situated in the Natuna Sea in the southern part of the South China Sea, are regarded as one of the remote areas of Indonesia. This archipelago comprises more than 200 small islands and boasts unique and intricate ocean features [17]. Given that most of the Anambas waters have been designated as marine protected areas, conducting a comprehensive assessment of its ecosystem condition is mandatory [11].

This study explores the potential of integrating remote sensing data with in situ measurements, specifically diameter at breast height (DBH), to create an estimation map for mangrove AGB across the Anambas Islands. Various approaches have been employed in Indonesia for similar purposes, including the utilization of active remote sensing [8, 18] and passive remote sensing data [2, 10, 19-23], the incorporation of active and passive remote sensing data [24], modeling using multi-source and multi-resolution data [25-26], and the application of Unmanned Aerial Vehichles (UAV) photogrammetry [15, 27]. However, none of these approaches have been documented as being applied in the Anambas region, despite field assessments of biomass and carbon stocks having been conducted in some parts of Anambas [11]. In this research, we will leverage vegetation indices derived from Sentinel-2 images along with in situ measurements to generate the first comprehensive map estimating mangrove AGB throughout the entire Anambas Islands.

2 Methods

This study was carried out in the Anambas Islands region (Figure 1). Most of the waters in the Anambas Islands have been designated as a national marine protected area, which is administered by the Indonesian Ministry of Marine Affairs and Fisheries. Mangroves, as an ecosystem in Anambas Islands, are spread across many islands throughout the region, but they are primarily found in bays where the waves and currents are relatively calm.

The Sentinel-2 image used in this study was acquired on 12 May 2023, during the same month as the field survey. Consequently, the likelihood of spatial displacement and temporal bias between in-situ data and the corresponding image pixel digital numbers (DN) is minimal. Sentinel-2 offers a variety of spectral bands with different spatial resolutions. It provides four bands with a 10-meter spatial resolution, encompassing the classical blue (490 nm), green (560 nm), red (665 nm), and near-infrared (842 nm). Additionally, there are six bands with 20-meter resolution, which consist of four narrow bands in the vegetation red-edge spectral domain (705 nm, 740 nm, 783 nm, and 865 nm) and two larger shortwave-infrared bands (1610 nm and 2190 nm). Furthermore, three 60-meter resolution bands are available for specific purposes: aerosol retrieval (443 nm), water vapor retrieval (945 nm), and cirrus cloud detection (1375 nm).

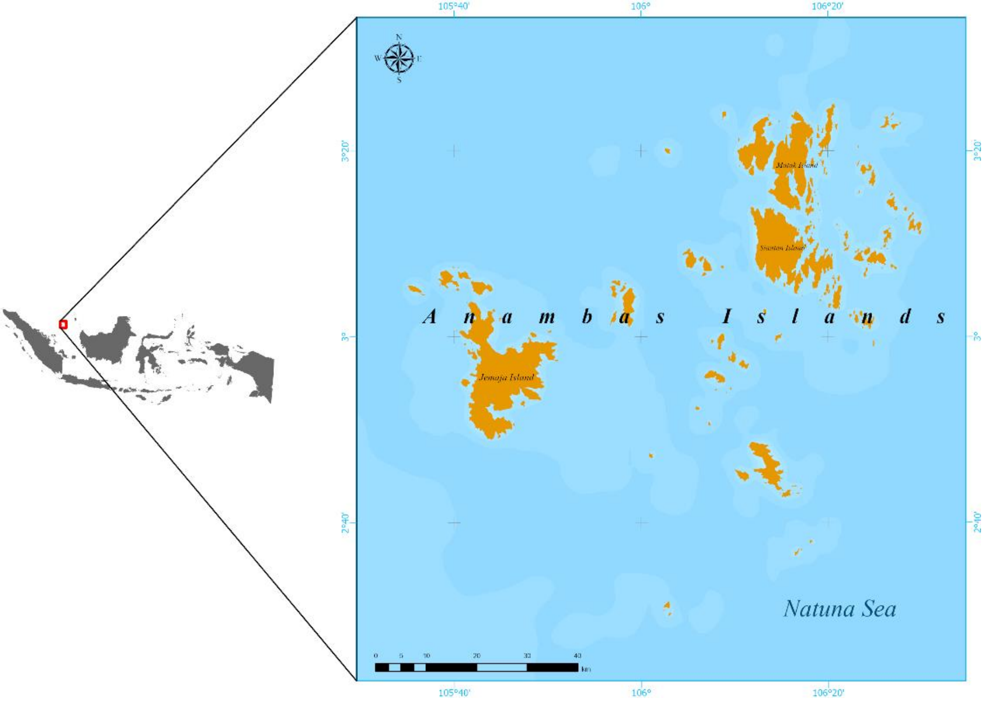

Fig. 1. Anambas Islands situation map

2.1 Field data measurements and analysis

A field survey was conducted from May 25th to May 31st, 2023. The survey employed a stratified random sampling technique to select locations for data collection. A total of 23 distributed mangrove samples were obtained, chosen for their accessibility, and their ability to represent the variation in substrate types within the study area (Figure 2). In this study, the assessment of AGB was derived from measuring the circumference of mangrove stands to calculate the diameter at breast height (DBH) within a plot size of 100 m2. The DBH values were subsequently employed in estimating AGB using the common allometric equation for all species [28], while species-specific wood density data were obtained from the World Agroforestry (ICRAF) database. The measurements of the mangrove stand circumferences were conducted as illustrated in Figure 3.

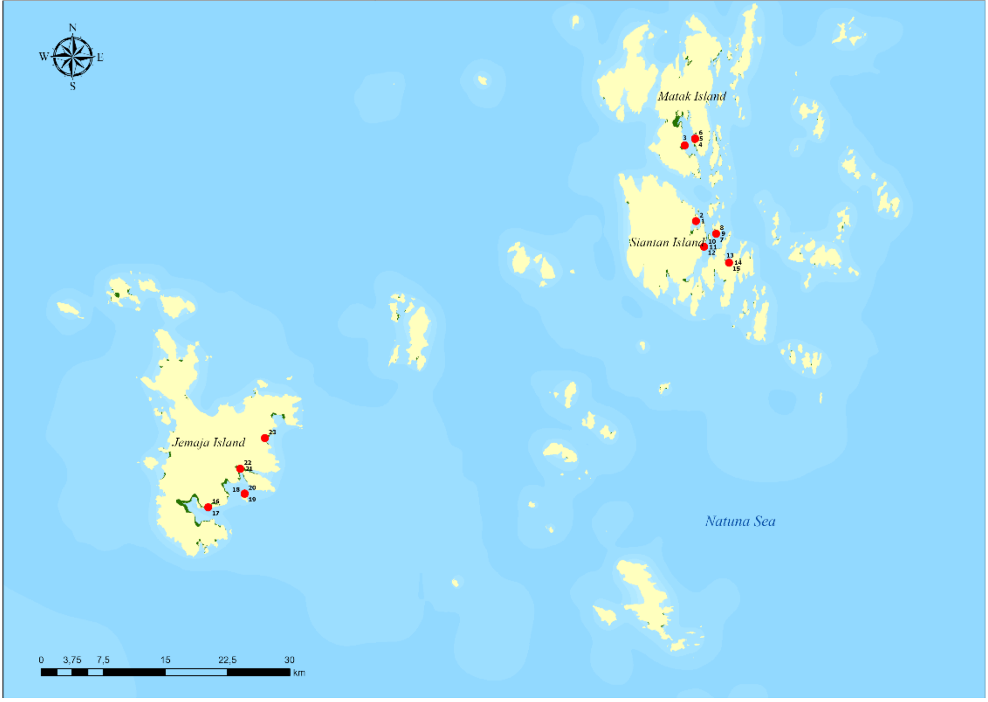

Fig. 2. Sample distribution of in situ measurements

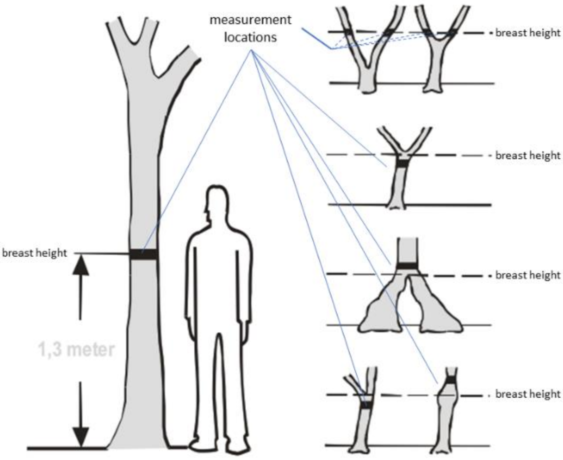

Fig. 3. Measurement guide in various conditions (with modifications) [29]

2.2 Mapping mangrove distribution

This study utilized Sentinel-2 products processed at Level-2A Collection 1. The Level-2A Collection 1 products provide orthorectified surface reflectance (Bottom-of-Atmosphere), ensuring precise alignment across multiple spectral bands and time periods at sub-pixel levels [30]. At this level of correction, an 8a-11-4 (Vegetation Red Edge-SWIR-Red) band composite was utilized to map mangrove distribution through visual interpretation. This particular color composite is considered the most effective RGB (red-green-blue) combination for Sentinel-2 imagery, as it accentuates the boundary between mangrove and non-mangrove areas [31]. The resulting mangrove distribution map was then utilized to mask out non-mangrove pixels for further analysis. All analysis were conducted using ArcGIS Pro software.

2.3 Vegetation indices transformation

Several vegetation indices were computed for mangrove areas using Sentinel-2 images. Vegetation indices are commonly used image processing methods for modeling and mapping different aspects of vegetation in mangrove areas. These aspects include the Leaf Area Index (LAI), canopy coverage, biomass, and carbon stock [10]. In this study, seven indices utilizing visible and near-infrared bands with 10 m spatial resolutions on Sentinel-2 were computed on the ArcGIS Pro software: Simple Ratio (SR), Normalized Difference Vegetation Index (NDVI), Different Vegetation Index (DVI), Enhanced Vegetation Index (EVI), Visible Atmospherically Resistant Index (VARI), Modified Soil Adjusted Vegetation Index (MSAVI), and Global Environment Monitoring Index (GEMI) (Table 1).

Table 1. Vegetation indices utilized for mangrove AGB estimation.

Index	**Algorithm**	**Coeff.**	**Reference**
SR	$\frac{\rho_{red}}{\rho_{NIR}}$		[32-33]
NDVI	$\frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}}$		[34]
DVI	$\rho_{NIR} - \rho_{red}$		[34]
EVI	$G \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + C_1 \times \rho_{red} - C_2 \times \rho_{blue} + L}$	*L = 1* *C_1 = 6* *C_2 = 7.5* *G = 2.5*	[35]
VARI	$\frac{\rho_{green} - \rho_{red}}{\rho_{green} + \rho_{red} - \rho_{blue}}$		[36]
MSAVI	$\frac{2\,\rho_{NIR} + 1 - \sqrt{(2\,\rho_{NIR} + 1)^2 - 8(\rho_{NIR} - \rho_{red})}}{2}$		[37]
GEMI	$\eta(1 - 0.25\eta) - \frac{\rho_{red} - 0.125}{1 - \rho_{red}}$ Where $\eta = \frac{2({\rho_{NIR}}^2 - {\rho_{red}}^2) + 1.5\rho_{NIR} + 0.5\rho_{red}}{\rho_{NIR} + \rho_{red} + 0.5}$		[38]

2.4 Mangrove AGB modelling

Vegetation indices, along with AGB value obtained from allometric assessment, were utilized as inputs for modeling Anambas mangrove AGB. Regression analysis was employed to predict mangrove AGB. In addition to linear regression, we also assessed the performance of exponential, logarithmic, polynomial (second order), and power/geometric regression models. This approach has been previously applied in mangrove carbon stock modeling in Pamekasan, East Java, Indonesia [39].

The error and accuracy of AGB prediction were measured using a standard error of estimation (SEE) equation. The accuracy rate was generated by converting the error into error percentage using the 95% confidence level (95%CL) value. This approach calculates the minimum and maximum possible accuracy of prediction within 95% CL [40].

3 Results and Discussion

3.1 Anambas Islands AGB assessment

The aboveground biomass (AGB) of mangroves was calculated using an allometric equation. This approach relies on the measurement of the Diameter at Breast Height (DBH) of mangrove stands, which were collected during a field survey. During this survey, we identified ten species within 23 sample plots. These species include *Aegiceras floridum*, *Avicennia marina*, *Bruguiera gymnorrhiza*, *Bruguiera sexangula*, *Ceriops tagal*, *Rhizophora apiculata*, *Rhizophora xlamarckii*, *Rhizophora mucronata*, *Rhizophora stylosa*, and *Xylocarpus granatum*.

The AGB calculation revealed AGB values ranging from 589.29 kg (for plot 2) to 5515.35 kg (for plot 16) per 100 m^2 of plot area (see Table 2). Biomass (including carbon) production in mangroves appears to be influenced by various factors, including location-specific characteristics like soil and substrate type, tidal and salinity regimes, as well as species composition [41]. Soil containing a greater proportion of fine particles has the capacity to retain more water compared to sandy soils, and with more silt or clay content, it can offer greater stability and support for the roots in contrast to sandy soils [42].

Through substrate type assessments using the "feel method" [43], we identified three substrate types at our study location: loamy sand, sandy loam, and silt loam. Some plots with loamy sand substrate exhibited high AGB values, primarily due to the prevalence of *Rhizophora sp.*, in these areas, which tend to exhibit greater AGB production in environments with lower concentrations of silt or clay [42].

Table 2. AGB values in sample plots.

Plot	AGB (kg/100m^2)	Number of stands	DBH average (cm)	Substrate types
1	637.91	59	4.62	Sandy loam
2	589.29	38	5.28	Sandy loam
3	1028.76	48	5.85	Sandy loam
4	1990.04	71	6.17	Loamy sand
5	1643.83	53	7.10	Loamy sand
6	3076.61	68	8.01	Loamy sand
7	1123.40	82	4.97	Loamy sand
8	1641.83	147	4.49	Loamy sand
9	954.70	61	5.24	Loamy sand

10	1310.32	52	6.15	Loamy sand
11	1576.37	68	5.85	Loamy sand
12	1842.80	71	5.40	Loamy sand
13	1783.85	51	7.22	Sandy loam
14	3768.18	48	8.96	Sandy loam
15	1884.47	75	6.00	Sandy loam
16	5515.35	54	6.84	Sandy loam
17	4168.38	41	5.40	Sandy loam
18	3591.42	37	8.40	Loamy sand
19	4788.56	69	7.04	Loamy sand
20	4187.06	51	8.48	Loamy sand
21	4310.68	126	4.47	Silt loam
22	3206.95	109	4.30	Silt loam
23	4503.51	23	10.93	Loamy sand
Average	**2570.62**	**65**	**6.40**	

3.2 Anambas Islands AGB mapping

Seven vegetation indices were employed to model and estimate AGB in the Anambas Islands. For each index, five regression analyses were performed to select the most suitable model for predicting AGB value. As shown in Table 3, R^2 (coefficient of determination) values for the seven vegetation indices and five regression methods ranged between 0.0845 (VARI-exponential) and 0.6659 (MSAVI-polynomial). In comparison to the previous study conducted in Indonesia, our value is lower than the AGB model on ALOS-2 PALSAR-2 images [8,18], but it surpasses the studies in Mandeh Bay using Landsat 8 images [22] and the study in Bedul Mangrove Block using level-3B PlanetScope images [23].

The accuracy of the mangrove AGB prediction spanned from 34.56% (VARI-linear) to 72.09% (MSAVI-polynomial). Notably, MSAVI consistently demonstrated the highest accuracy across the five regression methods in this study. Consequently, the MSAVI polynomial regression analysis was employed to create a model and estimate the AGB map of the Anambas Islands, with a standard error (SE) of 2.56 kg m^{-2}. This accuracy is approximately 5% lower than that of a previous study in Karimunjawa [10], and also lower than the estimation on a higher resolution image in Teluk Benoa (80.95%) [20], but much higher than estimation in Perancak Estuary (42.71%). In this study, we observed that the use of nonlinear regression may improve the R^2 and accuracy of the model. These findings were also demonstrated in the study of carbon stock models in Indonesian Papua [24] and Pamekasan [39].

The good performance of the MSAVI in this research, as demonstrated in other studies conducted in Vietnam for predicting biomass, surpasses that of NDVI [44]. MSAVI has also been effectively employed to detect changes in AGB through the utilization of red and NIR reflectances [45]. This index, an enhancement of SAVI, possesses the capability to mitigate background soil reflectance in canopy spectra [44]. Consequently, MSAVI stands out as one of the most suitable indices for regions characterized by sparse vegetation [46].

On the other hand, in this study, VARI serves as the sole index utilizing green reflectance and demonstrates the weakest performance when compared to the other indices. Furthermore, the absence of NIR reflectance in the VARI equation may also be a contributing factor to this outcome. This condition also arises in a study conducted in the Karimunjawa Islands to model mangrove carbon stock. The study expounds that relying on a vegetation index solely based on visible bands, such as VARI, is not recommended and results in poorer performance [10].

In addition to MSAVI, other vegetation indices that have demonstrated strong performance include EVI, DVI, NDVI, and SR. These indices consistently achieve accuracy levels ranging from 59.15% to 71.84% across five regression methods. The effectiveness of these indices in mapping mangrove biomass has also been highlighted in previous studies, such as EVI and NDVI in Karimunjawa [40], and DVI in the Segara Anak River [23].

Table 3. Results of mangrove AGB modelling in Anambas using Sentinel-2.

Vegetation Indices	Regression method	R^2	SE (kg m^{-2})	Max. Accuracy
SR	Linear	0.3310	1.80	60.50
	Exponential	0.4142	1.34	60.20
	Logarithmic	0.3951	1.97	62.44
	Polynomial	0.5064	2.23	66.08
	Power	0.4806	1.53	62.55
NDVI	Linear	0.3681	1.90	61.62
	Exponential	0.4555	1.44	61.57
	Logarithmic	0.3020	1.72	59.66
	Polynomial	0.5289	2.28	66.86
	Power	0.3782	1.27	59.15
DVI	Linear	0.4823	2.18	65.26
	Exponential	0.5814	1.75	66.11
	Logarithmic	0.3709	1.91	61.70
	Polynomial	0.6297	2.49	70.62
	Power	0.4778	1.42	61.91
EVI	Linear	0.4744	2.16	64.99
	Exponential	0.5926	1.70	66.13
	Logarithmic	0.3672	1.90	61.59
	Polynomial	0.6598	2.54	71.84
	Power	0.4813	1.40	61.88
VARI	Linear	0.1069	1.02	34.56
	Exponential	0.0845	1.05	52.07
	Logarithmic	0.1240	1.10	54.81
	Polynomial	0.1345	1.15	55.08
	Power	0.1131	0.99	52.87
MSAVI	Linear	0.5294	2.28	66.88
	Exponential	0.6274	1.88	68.08
	Logarithmic	0.5086	2.23	66.15
	Polynomial	0.6659	2.56	72.09
	Power	0.6156	1.80	67.33
GEMI	Linear	0.4141	2.02	29.29
	Exponential	0.5104	1.56	63.38
	Logarithmic	0.3845	1.94	62.12

	Polynomial	0.5757	2.38	68.55
	Power	0.4821	1.47	62.28

The polynomial equation generated through regression analysis of MSAVI pixel values and field AGB data was employed to estimate AGB for the Anambas Islands with equation $AGB(kg/100m^{-2}) = 139{,}862(MSAVI)^2 - 217{,}603(MSAVI) + 85{,}578$. This analysis revealed that the approximated mangrove AGB in the Anambas Islands amounts to 369,371.47 tonnes, distributed across 1,097.43 hectares of mangrove coverage. Assuming a 47% concentration of carbon in the biomass [47], the estimated carbon stock for Anambas Islands' mangroves stands at 173,604.59 tonnes.

A prior estimation conducted in the Anambas Islands Marine Tourism Park found that the total biomass (above-ground and below-ground) was 574.73 tonnes per hectare, with a carbon stock of 270.12 tonnes per hectare [11]. Using the same mangrove area, the Anambas Islands' biomass and carbon stock would be 630,725.94 tonnes and 296,437.79 tonnes respectively, which is 1.7 times higher than the estimation in this study. This discrepancy may be attributed to the fact that this research solely focused on aboveground biomass, while the previous study included below-ground assessment. In addition, the dissimilarity in results can be attributed to the previous study's simple calculation of the average biomass value based on field data assessment, whereas this study has estimated biomass with consideration of spatial variation in pixel area.

Figure 4 displays a map illustrating the distribution of mangrove AGB in the Anambas Islands. Geographically, the Anambas consists of numerous small islands, which presents a challenge in terms of exposing the mangrove areas. These mangroves are scattered across various small areas throughout the region. Some of the islands have bays that provide favourable conditions for mangrove growth due to their calmer waters, such as Matak Island, Jemaja Island, and Keramut Island.

The map clearly highlights the spatial variations in estimated AGB across the Anambas Islands. Notably, one of the highest AGB values is observed in the mangroves located within the bay of Matak Island, where estimates exceed 60 kg m^{-2}. This information holds significant value for regional conservation strategies, including the determination of the protected zones, the establishment of a baseline of mangrove conditions, and the assessment of carbon credits.

This research will mark one of the initial investigations into mangrove biomass mapping in the Anambas Islands. Future studies should expand to include an analysis of below-ground biomass to comprehensively assess the total carbon stock in the Anambas region. The utilization of various passive and active remote sensing data and methods is highly recommended for achieving higher accuracy.

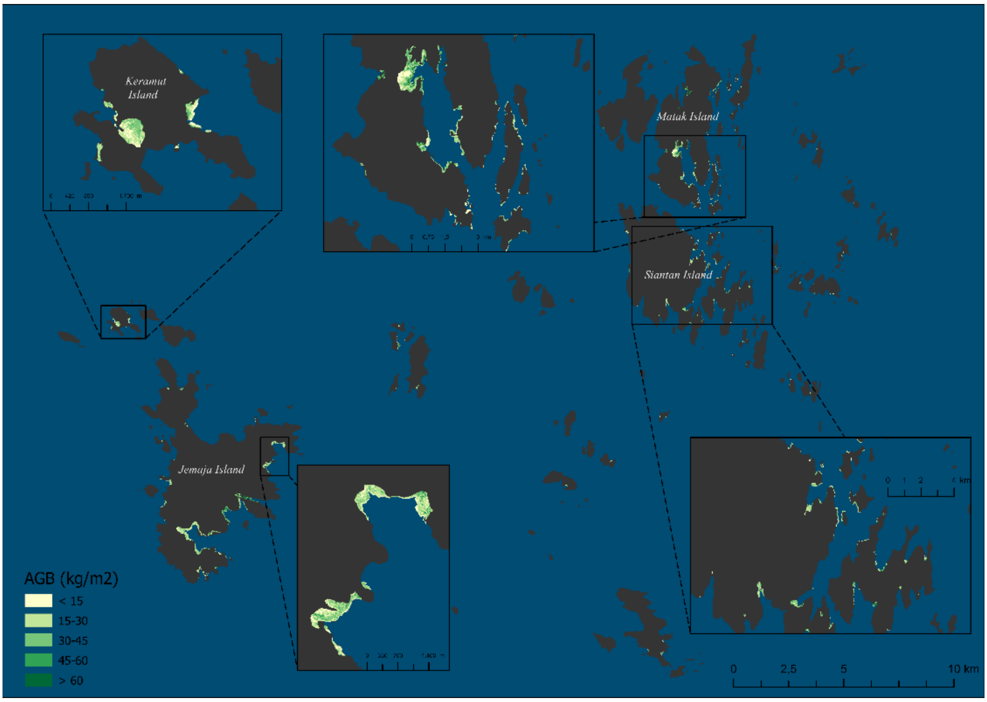

Fig. 4. Mangrove AGB distribution modelled from Sentinel-2 with 72.09% accuracy

Conclusion

In conclusion, the incorporation of Sentinel-2 images and field survey data demonstrates its capability to map mangrove AGB in the Anambas Islands. The highest accuracy achieved is 72.09%, utilizing polynomial regression analysis with MSAVI as the independent variable and AGB values derived from field data as the dependent variable. Additionally, this study highlights the potential of other vegetation indices such as EVI, DVI, NDVI, and SR, which performed well in estimating AGB in the Anambas Islands. Through this model, we have successfully estimated the AGB to be 369,371.47 tonnes and the carbon stock to be 173,604.59. It is important to note that estimating AGB using remote-sensing data offers valuable insights into spatial variations and distributions that cannot be solely derived from field data measurements. Future research should focus on expanding the analysis to include below-ground biomass and incorporating different remote-sensing data and methods to further enhance accuracy.

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