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Mapping above-ground carbon of mangroves using Sentinel-2 satellite imagery in the east coast of North Sumatra Province, Indonesia

ACHMAD SIDDIK THOHA[1,♥], PURWANTO[2], PIPIT WIJAYANTI[3], RITA NOVIANI[3], RAVINESH ROHIT PRASAD[4], SHOFIA PUTRI NASIBAH[1]

[1]Faculty of Forestry, Universitas Sumatera Utara. Jl. Lingkar USU, Durin Tunggal, Pancur Batu, Deli Serdang 20353, North Sumatra, Indonesia. Tel./fax.: +62-820-1920, ♥email: a.siddik@usu.ac.id

[2]Department of Geography, Faculty of Social Sciences, Universitas Negeri Malang. Jl. Semarang No. 5, Lowokwaru, Sumbersari, Malang 65145 East Java, Indonesia

[3]Faculty of Teacher Training and Education, Universitas Sebelas Maret. Jl. Ir. Sutami No.36 A, Kentingan, Jebres, Surakarta 57126, Central Java, Indonesia

[4]Department of Social Sciences, Fiji National University. Lautoka, Fiji

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Abstract. *Thoha AS, Purwanto, Wijayanti PW, Noviani R, Prasad RR, Nasibah SP. 2025. Mapping above-ground carbon of mangroves using Sentinel-2 satellite imagery in the east coast of North Sumatra Province, Indonesia. Biodiversitas 26: 3916-3925.* Accurate estimation of carbon stocks in mangrove ecosystems is essential for assessing blue carbon potential. Conventional methods using field surveys to estimate Above-Ground Carbon (AGC) require significant amount of time and costs. Mangrove carbon stock can be calculated quickly and cost-effectively by utilizing satellite technology and publicly available data. The purpose of this study is to determine the best model for estimating AGC in mangrove forests managed by community in east coast of North Sumatra, Indonesia, using Sentinel-2 Imagery. The study was conducted on two different mangrove conditions following community-led restoration efforts, i.e. mangrove forest planted with a single species of *Rhizophora mucronata*, and restored mangrove forest consisted of 6 tree species. Field-measured AGC was estimated using the allometric equation of tree Diameter at Breast Height (DBH) and used as dependent variable. Sentinel-2 satellite imagery was used to derive several vegetation indices using reflectance values, which were used as independent variables. Several carbon estimation models were developed and validated with the best model was those with the lowest error and the highest coefficient of determination (R^2). It was discovered that the model that employed Normalized Difference Vegetation Index (NDVI) and Total Ratio Vegetation Index (TRVI) was the best for estimating AGC in monospecies mangroves, while the model that employed NDVI and Inverted Red Edge Chlorophyll Index (IRECI) was the most accurate when estimating AGC in multispecies mangroves. In monospecies mangrove forest, AGC estimate ranged 0-200 Mg/Ha, while in multispecies mangrove forest, the estimate ranged 0-400 Mg/Ha. The higher AGC estimates in multispecies forests indicate that a more diverse mangrove species has a higher carbon sequestration capacity than homogeneous forests. The findings of this study indicate that AGC mapping using Sentinel-2 Imagery also supports blue carbon initiatives, mangrove ecosystem service assessments, and conservation-based policy-making.

Keywords: Above-ground carbon, blue carbon, mangrove, North Sumatra, vegetation index

INTRODUCTION

As the primary ecosystem in coastal regions, mangrove forests contribute significantly in delivering ecosystem services essential to human and other living organisms. Mangrove forests provide various ecosystem functions in coastal areas, including serving as the habitat of aquatic biota (Sihombing et al. 2017; Onrizal et al. 2020), preventing abrasion along the coastlines (Nordhaus et al. 2019; Sadono et al. 2020), offering ecotourism locations (Pin et al. 2021), storing carbon (Widyastuti et al. 2018; Fourqurean et al. 2019; Kusumaningtyas et al. 2019; Sidik et al. 2019; Matatula et al. 2021), providing foods (Arbiastutie et al. 2021), and protecting coastal region from tsunami, waves and storms (Onrizal and Mansor 2016). Mangrove forest is among the ecosystems with the largest carbon sinks globally, thus the preservation of mangrove forests is key to climate change mitigation (Murdiyarso et al. 2015). This can be done by preventing the conversion of mangrove forests to other land uses (Eddy et al. 2017), preventing adverse socio-economic impacts of human activities (Basyuni et al. 2018) and increasing blue carbon resilience (Purwanto et al. 2025). Converting mangrove forest to other land uses results in greater CO_2 emissions than sequestration (Eddy et al. 2021).

The primary causes of mangrove deforestation and degradation are human activities, including urbanization, timber extraction and conversion of mangrove forest into ponds for shrimp or fish farming (Richards and Friess 2016). Murdiyarso et al. (2015) show that mangrove forest loss and degradation alone contribute to 42% of Southeast Asia's global carbon dioxide (CO_2) emissions. One of the most threatened mangrove ecosystems in Southeast Asia is located along the coast of North Sumatra Province, Indonesia. According to the Mangrove and Peatland Restoration Agency (BRGM), the current extent of mangroves in North Sumatra is 57,490 hectares, with 8,878 hectares in degraded condition, mostly located in fish pond areas and newly formed lands as a result of sediment deposition (Antaranews 2024).

Efforts to address CO_2 emissions require an understanding on the carbon sequestration capacity of mangrove forests. This can be achieved by estimating the total carbon stock stored in mangrove biomass (Hastuti et al. 2017; Suardana et al. 2022). There are several methods for estimating carbon in mangrove ecosystem using field-based approach, remote sensing or the combination of both, and each method has particular advantages and limitations. Nevertheless, according to Heumann (2011), combining mangrove biomass estimation data with remote sensing is the best and most practical method. This integration generates an allometric equation that forms the basis for the mangrove carbon stock estimation model (Patil et al. 2015).

Several studies on mangrove ecosystem mapping using remote sensing in North Sumatra have been conducted, including those by Thoha et al. (2002) and et al. (2024). More recently, Basyuni et al. (2023) and Thoha et al. (2024) carried out detailed investigations using drone technology to estimate Above-Ground Carbon (AGC) in mangrove forests. However, these drone-based studies have been limited in spatial coverage and require substantial time for data processing. As a result, large-scale mapping using drones remains a challenge. Prior study by Dewanti et al. (2020) employed field-based approach by systematic sampling techniques but encountered costly and time-consuming processing. In contrast, Mahasani et al. (2021a, b) used ALOS PALSAR satellite imagery and produced results with moderate precision.

Calculating AGC in mangrove ecosystem, especially in the North Sumatra coast, is essential to gather information on the significant value of mangroves in providing ecosystem services. The AGC carbon data is essential to support mangrove restoration efforts given the high AGC potential of mangroves that can contribute to carbon emission reduction programs from the forestry sector. Since field surveys to estimate AGC are time-consuming and costly, freely accessible satellite technology can be used to calculate AGC in mangrove quickly and inexpensively. With increasingly comprehensive above-ground carbon stock data, various stakeholders are expected to increase support in mangrove forest restoration and conservation efforts.

Therefore, this study aims to determine effective model for estimating AGC in mangrove forests using multispectral and vegetation index of satellite imagery data, particularly in North Sumatra's Forest restoration area. In doing so, this study employs Sentinel-2 Imagery on mangrove forest managed by a community in North Sumatra's east coast. Estimation of AGC in community forests on the coast of North Sumatra using satellite imagery are still very limited in terms of data and measurement techniques. To develop most effective technique for estimating mangrove AGC, this study combines a semi-empirical methodology with multispectral readings and vegetation indices.

MATERIALS AND METHODS

Study area and period

The study was located in the restored mangrove forests in Brandan Barat Sub-district, Langkat District and Lima Puluh Pesisir Sub-district, Batubara District in North Sumatra Province, Indonesia (Figure 1).

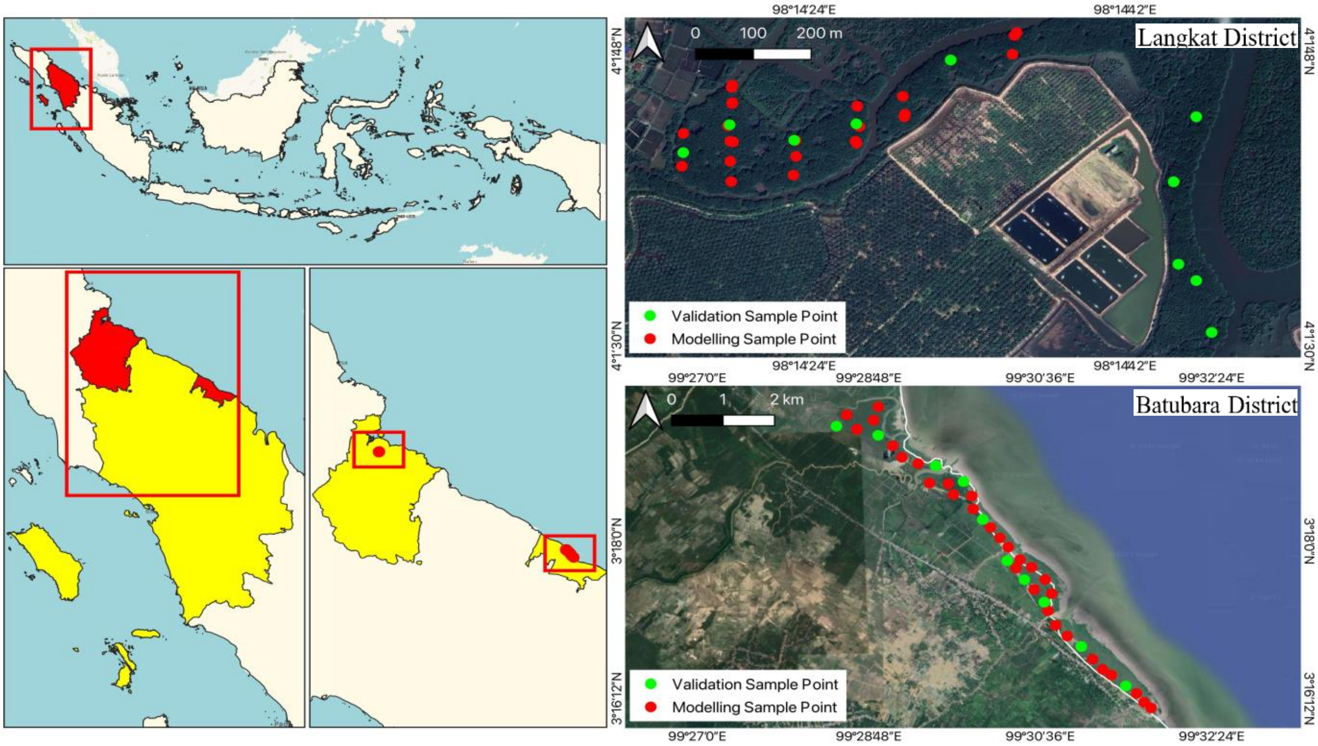

Figure 1. Study area and vegetation survey sites in North Sumatra Province, Indonesia: Batubara District with multispecies mangrove (right-bottom) and Langkat District with single species (right-top)

The mangrove forest in Langkat District is the result of a community-led mangrove restoration project, with tree planting beginning in 2019. On the other hand, the forest in Batubara District is a secondary mangrove resulting from restoration efforts initiated in 2010. Mangrove restoration efforts in Batubara District were carried out due to mangrove damage that occurred prior to 2010. Mangroves in Batubara District were damaged by coastal sand mining and tidal flooding that inundated villages prior to 2010. Meanwhile, in Langkat, mangrove restoration efforts are underway to restore mangrove forests damaged by uncontrolled logging and the expansion of fish ponds. Fieldwork was carried out between June to August 2024.

Procedure

The research data used in this study included Sentinel-2A imagery accessed through Google Earth Engine (GEE), administrative boundary maps from the Geospatial Information Agency, and forest area maps from the North Sumatra Provincial Forestry Service. Data on tree species and diameter were collected through field surveys using 10x10 m^2 sample plots with a total of 40 plots in each location. Thirty points were used to build the model, and 10 points were reserved for model validation (Figure 1). Point locations were selected based on accessibility and forest condition representation.

Data analysis

Sentinel-2A imagery was processed using Google Earth Engine (GEE). The Random Forest (RF) approach was employed to classify mangrove and non-mangrove areas. Following the classification, a semi-empirical method was used to map and evaluate AGC of mangrove. The AGC was calculated and produced for each species using allometric equation. Before calculating AGC, Above-Ground Biomass (AGB) for each species was estimated using allometric equations designed for Asian mangroves (Table 1), making them highly applicable for use in Indonesia. The biomass of mangroves was determined using allometric equations based on Diameter at Breast Height (DBH) (Kumar and Mutanga 2017). AGC was estimated by multiplying AGB by 0.47 following the Indonesian National Standard (SNI 7724:2011) and Fourqurean et al. (2019).

A linear regression model was used to estimate AGC for a single independent variable, while a multiple regression model was used for multiple independent variables. AGC served as the dependent variable, whereas the independent variables consisted of reflectance values from individual Sentinel-2 bands and vegetation indices calculated using the formulas presented in Table 2. The best model was selected based on the combination of variables that produced the highest correlation value.

Table 1. Allometric equations used in this study to determine Above-Ground Biomass (AGB)

Species	Equation	Wood density (ρ)[a]	Reference
Avicennia marina	$0.308 * D^{2.11}$	0.732	Comley and McGuinness (2005)
Rhizophora stylosa	$0.1579 * D^{2.593}$	0.940	Analuddin et al. (2020)
Sonneratia caseolaris	$0.04975 * D^{1.94748}$	0.534	Hanh et al. (2016)
Xylocarpus granatum	$0.0823 * D^{2.59}$	0.528	Tarlan (2008)
Excoecaria agallocha	$0.251 * D^{2.46}$	0.450	Komiyama et al. (2008)
Rhizophora mucronata	$0.143 * D^{2.519}$	0.8483	Analuddin et al. (2018)

Note: D: Tree DBH (cm), ρ: Wood density (g cm^{-3})

Table 2. Vegetation index equations used to develop the Above-Ground Carbon (AGC) model for mangroves

Vegetation indices	Equations	References
Normalized Difference Vegetation Index (NDVI)	$NDVI = \frac{NIR-Red}{NIR+Red}$	Ramdani et al. (2018) and Pham et al. (2018)
Modified Red Edge Simple Ratio (mRE-SR)	$mRE\text{-}SR = \frac{\left(\frac{NIR}{Red\ Edge}\right)-1}{\sqrt{\left(\frac{NIR}{Red\ Edge}\right)+1}}$	Pu and Landry (2012) and Zhu et al. (2017)
Difference Vegetation Index (DVI)	DVI = NIR – Red	Hong-Wei et al. (2019)
Inverted Red Edge Chlorophyll Index (IRECI)	$IRECI = \frac{(NIR-Red)}{\left(\frac{Red\ Edge\ 1}{Red\ Edge\ 2}\right)}$	Clevers et al. (2001)
Red-Edge Simple Ratio (SRre)	$SRre = \frac{NIR}{Red\ Edge}$	Hallik et al. (2019)
Chlorophyll Index Red Edge (Clre)	$Clre = \left(\frac{NIR}{Red\ Edge}\right) - 1$	Gitelson et al. (2003) and Gitelson et al. (2006)
Total Ratio Vegetation Index (TRVI)	$TRVI = \sqrt{\frac{NIR}{Red}}$	Fadaei et al. (2012)

RESULTS AND DISCUSSION

Identification and characteristics of mangrove forests

The satellite imagery used was a cloud-free composite of Sentinel-2 images dated January-December 2024. The detected mangrove area at the study site covered approximately 212.62 hectares in Langkat District and 413.82 hectares in Batubara District (Figure 2). The locations of the mangrove forests differ between the two study sites where in Langkat District. The study area is some distance from the coastline, whereas Batubara District is located directly on the coast.

The Random Forest (RF) classification method yielded excellent results for distinguishing mangroves and non-mangroves, with a Kappa Accuracy of 0.961 and an Overall Accuracy (OA) of 0.984. Specifically, the classification for the two study locations achieved an overall accuracy of 95-96% and a Kappa coefficient ranging from 87% to 90%, indicating strong classification accuracy. These high accuracy values correspond well with previous Sentinel-2 classification studies and field data validation (Dan et al. 2016). The high accuracy values are due to tidal duration, low cloud cover, uniform sample point selection (Dong et al. 2020), and only discriminate two classes of vegetation (i.e., mangroves and non-mangroves) (Nguyen et al. 2020). When detecting mangrove forests, the RF classification method with multi-parameter sensitivity significantly increases accuracy.

The two studied areas had different characteristics. The mangrove forest in Langkat District is located at a river estuary with some distance from the coast, while the mangrove forest in Batubara District is located along the coastline (Figure 2). In Langkat, the study area includes Lubuk Kasih Village and Pangkalan Batu Village, where *R. mucronata* dominated the mangrove vegetation. These two villages have a successful history of mangrove restoration in North Sumatra, resulting in dense mangrove forests with an average diameter above 10 cm, covering 212.64 hectares. In Langkat, the status of the forest area is production forest managed by the government, but mangrove restoration is carried out by the community. In Batubara, the status of the area is protected forest, where land management and restoration are carried out by the social forestry management unit.

In Batubara District, the studied mangrove forest occured in Perupuk Village and Gambus Laut Village, where the mangrove vegetation was dominated by *A. marina*. Other species found include *R. stylosa*, *S. caseolaris*, *X. granatum*, and *E. agallocha*. These villages also have a successful history of mangrove restoration, resulting in dense forests with an average diameter above 10 cm. The mangrove study area covers 421 hectares, managed by the Cinta Mangrove Forest Farmer Group. This area is a community forest (HKm) under a management license from the Indonesian Ministry of Environment and Forestry (KLHK).

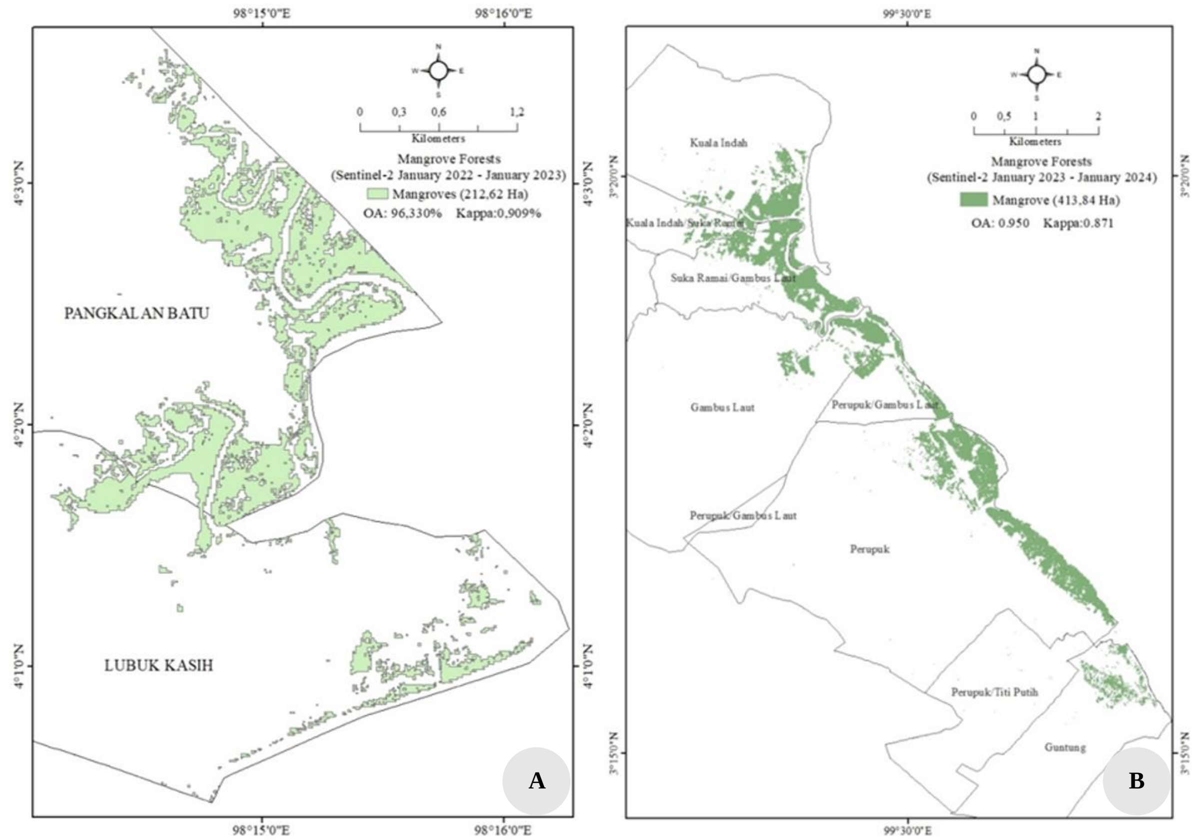

Figure 2. Area of mangrove forest derived from Sentinel-2 dated January-December 2024 on the eastern coast of North Sumatra Province, Indonesia: A. Langkat District, B. Batubara District

Above-ground carbon of mangrove forest

The AGB and AGC calculations at each sample point from field measurement are displayed in Table 3 and Table 4. In the Langkat study area, only one mangrove species, *R. mucronata* was found in all observed sample points (Table 3), whereas 6 species were found in the Batubara area (Table 4).

Table 3 shows sample point 14 had the highest AGC (316.85 Mg/ha) among the sample points, while sample point 24 had the lowest AGC (47.38 Mg/ha) for the Langkat study site. In multispecies mangrove forest in Batubara District (Table 4), the highest AGC was recorded at sample point 37 (889.07 Mg/ha), whereas sample point 21 had the lowest AGC (2.49 Mg/ha).

Relationship between field-measured biomass and Sentinel-2 Imagery data

The correlation values between field-measured AGC and the Sentinel-2 multispectral bands (visible, red-edge, and infrared) are shown in Table 5. The correlation between AGC and the visible bands (blue, green, and red), red-edge 1, and SWIR is rather modest; in fact, the visible bands exhibit an inverse relationship. In the single-species mangrove forest in Langkat District, the association between AGC and the red-edge 2, red-edge 3, and NIR bands is greater with value ranging 0.73-0.88 (Table 5). Conversely, in the multispecies mangrove forest in Batubara District, the relationship between AGC and multispectral bands (Red-edge 2, Red-edge 3, and NIR) shows a lower correlation with AGC than the visible bands, ranging only from 0.69-0.84. Meanwhile, in Batubara, the visible bands (red, green, and blue) show a stronger correlation with AGC with value ranging from 0.69-0.84 (Table 5).

Table 5 displays the correlation between field-measured AGC and different vegetation variables at both research sites. The red-edge and NIR bands, which are sensitive to vegetation identification, serve as the foundation for the employed vegetation indices (Imran et al. 2020). With a range 0.77-0.94, all vegetation indexes show a strong association with field-measured AGC.

Mapping predicted above-ground carbon stock

To estimate and map AGC values throughout the study area, the best model with the highest correlation value was selected. The best model to estimate AGC in mangrove forest in Batubara District employs vegetation indices of NDVI and TRVI from Sentinel-2 and presented as follow:

$$\boldsymbol{AGC} = 4813.739 + (-10045.468 \times \mathrm{NDVI}) + (1085.996 \times \mathrm{TRVI})$$

Whereas the best model to estimate AGC mangrove forest in Langkat District uses vegetation indices of NDVI and IRECI from Sentinel-2 and presented as follow:

$$\boldsymbol{AGC} = 39.032 + (257.074 \times \mathrm{NDVI}) + (-110.299 \times \mathrm{IRECI})$$

Figure 3.A presents AGC distribution map in Batubara District generated from Sentinel-2 Imagery using the Red and NIR bands (NDVI and TRVI). In the multispecies mangrove forest in Batubara District, these bands exhibit a strong relationship with AGC values. The AGC model which incorporated the combined NDVI and IRECI indices resulted in AGC value ranged from 0 Mg/ha to over 400 Mg/ha.

Figure 3.B illustrates AGC distribution map in Langkat District derived from Sentinel-2 Imagery using the Red and NIR bands (NDVI and IRECI). The AGC values in this region range 0-200.45 Mg/ha. This range is higher than the estimates reported by Mahasani et al. (2021a, b) and Suardana et al. (2023) for mangrove ecosystems in Bali, which ranged 0-234.55 Mg/ha and 0-163 Mg/ha, respectively.

Table 3. Above-Ground Biomass (AGB) and Above-Ground Carbon (AGC) calculations in mangrove forest in Langkat District, North Sumatra Province, Indonesia

Data grouping	Sample points	AGB (Mg/ha)	AGC (Mg/ha)	Dominant species
Model building (75%)	1	172.95	81.29	*Rhizophora mucronata**
	2	202.48	95.16	
	3	350.74	164.85	
	4	350.74	164.85	
	5	234.92	110.41	
	6	270.38	127.08	
	7	234.92	110.41	
	8	350.74	164.85	
	9	202.48	95.16	
	10	234.92	110.41	
	11	172.95	81.29	
	12	202.48	95.16	
	13	308.95	145.21	
	14	674.15	316.85	
	15	308.95	145.21	
	16	444.33	208.83	
	17	350.74	164.85	
	18	395.83	186.04	
	19	172.95	81.29	
	20	270.38	127.08	
	21	202.48	95.16	
	22	308.95	145.21	
	23	202.48	95.16	
	24	100.80	47.38	
	25	172.95	81.29	
	26	122.22	57.44	
	27	100.80	47.38	
	28	146.23	68.73	
	29	172.95	81.29	
	30	172.95	81.29	
Model validation (25%)	31	172.95	81.28	*Rhizophora mucronata**
	32	202.47	95.16	
	33	172.95	81.28	
	34	146.23	68.72	
	35	146.23	68.72	
	36	172.95	81.28	
	37	100.80	47.38	
	38	65.28	30.68	
	39	122.22	57.44	
	40	100.80	47.38	

Note: *Only one species identified all sample point namely *R. mucronata*. Points 1-30 are model-building points, while points 31-40 are model validation points

Table 4. AGB and AGC calculations in mangrove forest in Batubara District, North Sumatra Province, Indonesia

Data grouping	Sample points	AGB (Mg/ha)	AGC (Mg/ha)	Dominant species
Model building (75%)	1	56.26	26.44	*Avicennia marina*
	2	44.86	21.08	*Avicennia marina*
	3	65.70	30.87	*Avicennia marina*
	4	54.26	25.50	*Avicennia marina*
	5	50.39	23.68	*Avicennia marina*
	6	180.44	84.81	*Avicennia marina*
	7	66.79	31.39	*Avicennia marina*
	8	102.77	48.30	*Avicennia marina*
	9	236.41	111.11	*Avicennia marina*
	10	65.70	30.87	*Avicennia marina*
	11	55.26	25.97	*Avicennia marina*
	12	62.46	29.36	*Avicennia marina*
	13	90.74	42.64	*Avicennia marina*
	14	207.43	97.49	*Avicennia marina*
	15	369.71	173.76	*Avicennia marina*
	16	79.48	37.36	*Avicennia marina*
	17	132.36	62.21	*Avicennia marina*
	18	98.67	46.37	*Avicennia marina*
	19	76.36	35.88	*Rhizophora mucronata*
	20	60.06	28.22	*Rhizophora mucronata*
	21	5.30	2.49	*Sonneratia caseolaris*
	22	512.37	240.81	*Rhizophora stylosa*
	23	419.40	197.11	*Xylocarpus granatum*
	24	478.03	224.67	*Excoecaria agallocha*
	25	260.96	122.65	*Excoecaria agallocha*
	26	301.24	141.58	*Excoecaria agallocha*
	27	72.42	34.03	*Avicennia marina*
	28	74.74	35.12	*Avicennia marina*
	29	115.30	54.19	*Xylocarpus granatum*
	30	336.53	158.17	*Xylocarpus granatum*
Model validation (25%)	31	74.74	35.12	*Avicennia marina*
	32	158.88	74.67	*Avicennia marina*
	33	411.52	193.41	*Avicennia marina*
	34	89.45	42.042	*Avicennia marina*
	35	106.96	50.27	*Avicennia marina*
	36	108.38	50.93	*Avicennia marina*
	37	1891.63	889.07	*Rhizophora stylosa*
	38	247.40	116.27	*Excoecaria agallocha*
	39	55.89	26.26	*Xylocarpus granatum*
	40	1826.76	858.57	*Rhizophora stylosa*

Based on the AGC distribution classes in Batubara District (Table 6), the largest AGC stock is found between 0-100 Mg/ha. This contrasts with the Langkat District. mangrove forest, where most areas are dominated by AGC stock above 200 Mg/ha. Notably, in Batubara, where mangrove restoration has been ongoing in this area since 2003, certain mangrove zones contain AGC stock exceeding 400 Mg/ha, covering nearly 40 hectares. Areas with AGC above 400 Mg/ha in Batubara District are sample points dominated by species such as *R. stylosa* (Figure 4), *X. granatum,* and *E. agallocha.* These tree species have a broad canopy and a diameter of over 20 cm, leading to higher biomass than other species.

Using the combined NDVI and IRECI indices to develop the model, the AGC class distribution in Langkat District. is shown in Table 7. The broadest AGC range is found in the class between 158-200 Mg/ha and above 200 Mg/ha. This indicates that most mangrove areas dominated by *R. mucronata* in Langkat (Figure 4) have significant above-ground carbon stock, generally exceeding 150 Mg/ha.

Discussion

The models that combined NDVI and other vegetation indices show a strong correlation with AGC in both Langkat District and Batubara District and with varying mangrove ecosystem conditions. AGC estimates range 0-200 Mg/ha in homogeneous mangrove forests, while in multispecies mangrove forests, AGC estimates have a greater degree of variability with range 0-400 Mg/ha. The higher AGC values in multispecies mangrove forests suggest that a greater diversity of mangrove species contributes to higher carbon absorption capacity compared to homogeneous stands.

The NDVI vegetation index is commonly used in mangrove forests to differentiate vegetation density and serve as a comparison to other vegetation indices to detect mangrove species in coastal areas (Ramdani et al. 2018). NDVI has proven more accurate for biomass and carbon stock estimation and mapping, as demonstrated by research in the Chure Region of the Sainamaina Municipality by Poudel et al. (2023). Recent studies by Suardana et al. (2023) on mangrove ecosystems in Bali, Indonesia, recommend the near-infrared band in the NDVI for blue carbon estimation models. These explanations show that carbon stock estimation models using NDVI and other vegetation indices can be applied to diverse mangrove conditions.

At all multispecies mangrove area in Batubara District, *A. marina* was the dominant species; however, the highest AGC values were recorded at points where *R. stylosa* was dominant. This result is consistent with studies conducted by Purnamasari et al. (2021) and Iksan et al. (2019), demonstrating that species from the *Rhizophora* genus consists of more carbon and biomass than other species. DBH, canopy cover, and biomass density all affect the mangrove stands' capacity in storing carbon (Suwa et al. 2021). Compared to sample points dominated by *A. marina*, those dominated by *R. stylosa* exhibited higher canopy cover as observed in the study area. It was assumed that AGB is strongly related to both wood density and tree diameter (DBH) when developing the model for estimating AGC. The amount of AGC stock in each tree is directly impacted by AGB values, suggesting a strong relationship between higher biomass and carbon storage (Purnamasari et al. 2021).

Estimates of AGC in monospecies forests in Langkat District show that the maximum value of carbon stocks is lower than in multispecies forests in Batubara District. In Batubara, multispecies mangrove forests demonstrate the potential to store over 400 Mg/ha of carbon. The study by Purwanto et al. (2021), which estimated carbon potential through field measurements, also found that AGC in multispecies forests was greater than in monospecies forests. Similarly, Wirabuana et al. (2021) found that multispecies community forests exhibited higher AGC values than those dominated by a single species. For example, the combination of *A. alba, R. mucronata* and *S. alba* has an AGC of 461 Mg/ha. This value is not much different from the AGC estimation using Sentinel-2 Imagery. This shows that using satellite imagery to estimate carbon potential in mangrove forests is reliable.

Table 5. Correlation between field-measured AGC and independent variables (predictors) derived from Sentinel-2

Modelling group	Predictor/s	Langkat		Batubara	
		Correlation with carbon, r	Observed and predicted, r	Correlation with carbon, r	Observed and predicted, r
Sentinel-2 multispectral bands	Red	-0.275	0.132	0.067	0.686
	Green	-0.364	0.318	0.026	0.686
	Blue	-0.239	0.088	0.100	0.843
	Red Edge 1	-0.482	0.531	-0.064	0.454
	Red Edge 2	-0.284	0.845	-0.037	0.220
	Red Edge 3	-0.375	0.771	0.007	0.258
	NIR	-0.196	0.727	-0.057	0.144
	SWIR	-0.14	0.628	-0.234	0.216
Sentinel-2 derived vegetation indices	NDVI	0.142	0.442	0.077	0.871
	TRVI	0.187	0.400	-0.011	0.792
	CIre	0.288	0.358	0.064	0.632
	IRECI	-0.048	0.836	0.033	0.641
	DVI	-0.167	0.731	-0.036	0.485
	mRE-SR	0.276	0.638	0.159	0.650
	SRre	0.288	0.428	0.059	0.632
Combination of sentinel-2 derived vegetation indices	NDVI, TRVI	-0.141	0.528	0.099	0.936
	TRVI, DVI	0.36	0.731	0.057	0.813
	IRECI, DVI	0.221	0.836	0.181	0.760
	NDVI, IRECI	0.289	0.864	0.071	0.882
	IRECI, TRVI	0.346	0.871	0.092	0.806

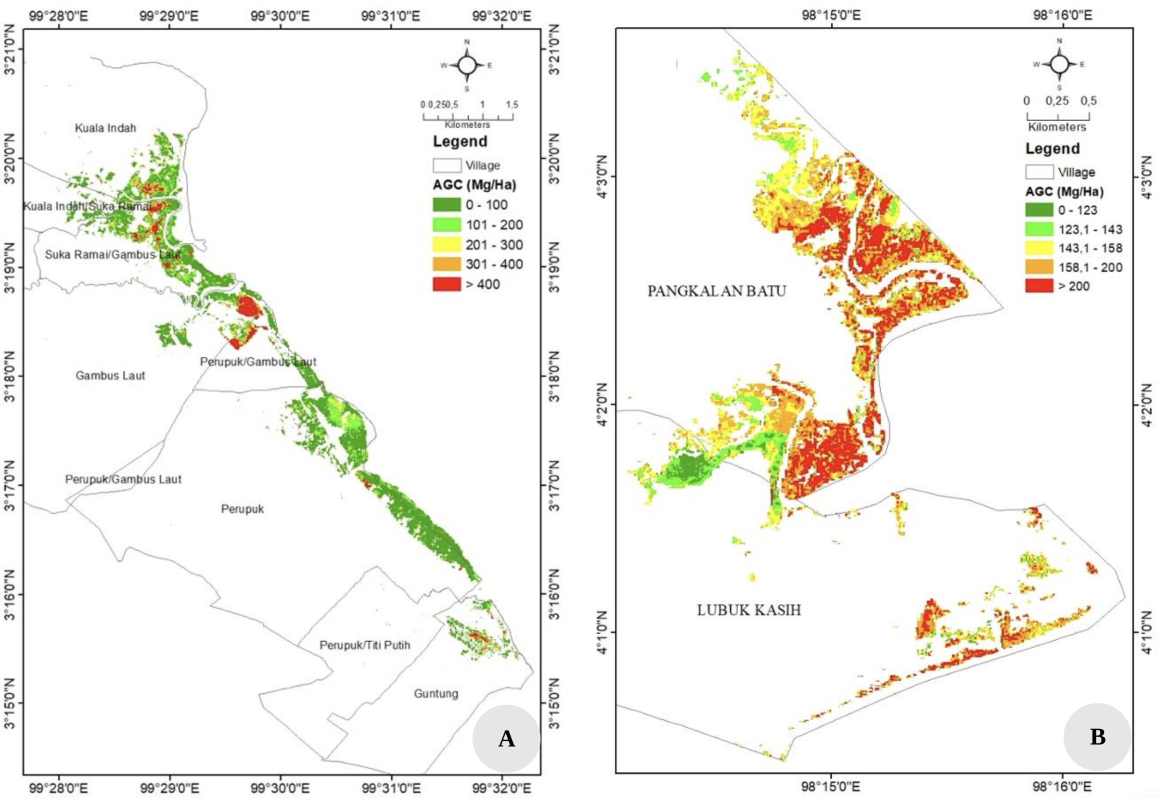

Figure 3. Predicted AGC distribution map at the study sites obtained from the best model from: A. Sentinel-2 NDVI and TRVI vegetation index in Batubara District, North Sumatra Province, Indonesia, B. NDVI and IRECI vegetation index in Langkat District, North Sumatra Province, Indonesia

Table 6. The distribution of AGC class modeled using NDVI and TRVI indices in mangrove forest in Batubara District, North Sumatra Province, Indonesia

Class	AGC range (Mg/ha)	Area (ha)
1	0-100	275.38
2	101-200	65.43
3	201-300	25.57
4	301-400	13.50
5	>400	39.62

Table 7. The distribution of AGC class modeled using NDVI and IRECI indices in mangrove forest in Langkat District, North Sumatra Province, Indonesia

Class	AGC Range (Mg/ha)	Area (ha)
1	0-123	10.74
2	123.1-143	25.38
3	143.1-158	58.22
4	158.1-200	79.85
5	>200	65.05

Figure 4. Condition of mangrove trees with the greatest AGC potential, i.e., A. *Rhizophora mucronata* in Langkat District, North Sumatra Province, Indonesia, B. *Rhizophora stylosa* in Batubara District, North Sumatra Province, Indonesia

In conclusion, the best models for estimating AGC stock in mangrove forests using Sentinel-2 satellite imagery were those that incorporate NDVI vegetation index. The combinations of NDVI and IRECI, and NDVI and TRVI show a strong correlation with AGC across two sites with varying mangrove vegetation conditions. Higher AGC estimates in multispecies mangrove forests indicate that multispecies mangrove species have greater carbon absorption capacity than monospecies forests. Carbon stocks in multispecies sites in study area are associated with denser mangrove tree growth and natural trees with large trunk diameters. Natural trees with large diameters serve as parent trees for seedlings and contribute large carbon stocks. Trees with large trunk diameters such as *R. stylosa* contributed the maximum carbon stocks of 858-889 Mg/ha.

Furthermore, the high AGC values recorded in both Langkat and Batubara highlight the success of community-led mangrove restoration initiatives. Having the evidence that successful mangrove restoration will contribute to increased carbon stocks will motivate stakeholders to get involved in the program. This highlights that mangrove restoration programs significantly contribute to reducing carbon emissions through blue carbon initiatives, which aim to restore degraded coastal ecosystems. The study also showed that multispecies restoration areas can provide higher carbon stocks.

Community-based Forest management has been proven to contribute significantly to ecosystem recovery, which is realized by the availability of carbon sequestration services from the mangrove forests they manage. The increase in mangrove carbon stocks as a result of successful mangrove restoration has both ecological and economic impacts. Ecologically, restored mangroves prevent coastal erosion and seawater intrusion, as well as restoring the habitat of coastal aquatic biota. The success of mangrove restoration in the study area in addition to increasing carbon stocks is also able to reduce the incidence of tidal floods. This shows that community initiatives have played a role in climate change mitigation. Economically, restored mangroves can provide several alternative livelihoods for fishermen generated from coastal marine resources. Therefore, support for mangrove ecosystem restoration efforts by the community on the North Sumatra coast should be strengthened, involving as many stakeholders as possible. Government policies to improve access and increase capacity for community-based mangrove ecosystem management need to be strengthened. Mangrove ecosystem restoration and conservation based on successful carbon stock enhancement in the study area needs to be encouraged for wider implementation in other locations.

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