Carbon stock mapping using mangrove discrimination indices in Mandeh Bay, West Sumatra

Erizal Mukhtar[1], Adityo Raynaldo[2], Wilson Novarino[1]

[1] Department of Biology, Faculty of Mathematics and Natural Sciences, Andalas University, Padang, West Sumatra, Indonesia; [2] Department of Marine Sciences, OSO University, Pontianak, West Kalimantan, Indonesia. Corresponding author: E. Mukhtar, erizalmukhtar@sci.unand.ac.id

Abstract. The mangrove discrimination indices can be used as variables in generating biomass models and mangrove carbon stocks. Through this approach, the spatial distribution of carbon stocks and the factors that influence them can be analyzed. The purpose of this study was to map the distribution of carbon stocks in the Mandeh area by formulating an AGC (Above Ground Stock) mangrove model from the existing mangrove discrimination index. A comparison of some MDI (mangrove discrimination indices) and NDVI (Normalized Difference Vegetation Index) commonly used in modeling was conducted, and the best model was determined through the regression coefficient and deviation values. The analysis shows that the mangrove index has the highest coefficient of determination and the lowest error. Carbon stock in Mandeh Bay was 8.32±0.08 mg ha^{-1}. Based on the results of potential carbon stock found, mangrove forest areas that the potential to be protected can be mapped.

Key Words: aboveground carbon stock, Landsat 8, mangrove, NDVI, vegetation indices.

Introduction. Mangrove forests have physical and ecological functions that are important for the preservation of ecosystems in coastal areas. Ecologically, mangrove forests function as nursery grounds, spawning grounds, and feeding grounds for a variety of aquatic biota such as fish, shrimps and crabs (Bosire et al 2003; Nagelkerken et al 2008). In addition, mangroves can reduce about 50% of the energy of tsunami waves (Mazda et al 1997a, 1997b). Currently, there is a concern about the reduction of mangrove areas.

Mangrove forests represent 2% of the world's forest area, but in terms of stored carbon reserves, mangrove forests have the highest carbon reserves, 30% of total forest carbon reserves (Alongi et al 2015) and can store up to four times more carbon (C) as than other tropical forests around the world (Donato et al 2011; Giri et al 2015). Carbon stocks in mangrove ecosystems generally have a wide value range, because mangrove ecosystems consist of zones that have various structures and composition of species (Martuti et al 2017; Harishma et al 2020). Various methods and research on carbon stocks in mangrove forests have been carried out, such as direct measurement by destructive and non-destructive means.

Indonesia has the most mangrove forests in the world (22.6% of the world's total mangrove area). However, the area of mangroves is decreasing yearly (FAO 2007). Degradation of mangrove forests in Indonesia is caused by various factors, including the conversion of mangrove forests to various development activities, dock building, as agricultural and plantation areas, as well as for oil and gas exploration activities (Kusmana 2012). However, research on mangrove ecosystems is still carried out, especially in the mangrove forest area of Sumatra.

Mangrove forests in West Sumatra Province are in varying conditions, both moderate and damaged. Pesisir Selatan District has the second largest mangrove forest, but the level of damage is in third place. Koto XI Tarusan District has the highest level of damage compared to other mangrove forest areas. On the other hand, this location has also been proclaimed by the Government as a natural tourism area known as the Mandeh Area (Bappeda 2017).

Remote Sensing (RS) satellites have been widely used for mangrove monitoring. There are several studies on the assessment of carbon stock in mangrove forests to accelerate the measurement methods used in wider forests. There are several techniques for monitoring mangrove forests using remote sensing, such as Landsat TM (Rakotomavo & Fromard 2010), Landsat TM and ETM+ (Li et al 2013; Nardin et al 2016), Landsat TM, ETM+ and OLI (Shapiro et al 2015; Giri et al 2015; Wang et al 2018a, 2018b), IKONOS (Satyanarayana et al 2011; Viennois et al 2016), and ALOS PALSAR (Lucas et al 2014; Abdel-Hamid et al 2018; Pham et al 2017). However, regional assessments of carbon stocks are still limited and should be reviewed for accuracy due to the great geographic variation in carbon stock in mangrove forests (Wang et al 2018; Pham et al 2019). In this research, we will modify and use a combination of the above methods.

There are several indices used as mangrove discrimination indices such as the mangrove index (Winarso & Purwanto 2014), Combined Mangrove Recognition Index (Gupta et al 2018), Mangrove Discrimination Index (Wang et al 2018a), and Modular Mangrove Recognition Index (Diniz et al 2019). The mangrove indices used have a good correlation with vegetation density and mangrove health (Winarso et al 2014). The above indices are suitable to be used as variables in generating biomass and distribution of mangrove carbon stocks models. However, using mangrove indices based on Winarso & Purwanto (2014) in determining biomass and carbon stocks has been scarcely conducted. Through the formulation of a carbon stock model with vegetation indices from Landsat imagery, the distribution of carbon stocks and their changes in an area can be analyzed.

Mandeh Bay is an ecotourism area that has been established by the Indonesian Government since 2010. By developing tourism businesses in this area, there will be many impacts, especially on the condition of mangrove forests. Based on the description above, a comprehensive research is needed on the mangrove forest area. Research in Mandeh Bay, West Sumatra, Indonesia, was started on the structure and composition of mangrove forests (Mukhtar et al 2017) and mapping and change analysis of mangrove forest by using Landsat imagery (Raynaldo et al 2020). Mapping the distribution of carbon stocks from all the Mandeh area is needed to provide comprehensive spatial information related to the impact of Mandeh area development on mangrove vegetation. This information can be used in strategies to plan the priorities of protected areas with high potential carbon stock.

Material and Method

Description of the study sites. Data was collected in June 2017 and July 2020 at three points in Mandeh Mangrove Forest, West Sumatra, Indonesia (Figure 1). The mangrove area in Mandeh Bay is the largest in South Pesisir Regency, the condition of the substrate being dominated by white sand substrate. The type of tide in this region is predominantly semi-diurnal, meaning that there are two tides in a day, but the height and time intervals are not the same.

Data and preprocessing. This study uses L1T Landsat 8 images that have been radiometrically and geometrically corrected on the acquisition date of 10 June 2019. Data was downloaded from the United States Geological Survey page (https://earthexplorer.usgs.gov/). Clipping of Mandeh area was based on Mandeh Tourism Area Planning (Bappeda 2017). The mangrove area from 2019 was determined using Landsat data with the same acquisition date. The false-color Landsat 8 composite approaches (RGB:564) were used according to the National Institute of Aeronautics and Space (2015) guidelines. The results of the ground check and supervised classification using the support vector machine had an overall accuracy value of 79.71%, with a mangrove area of 261.9 ha.

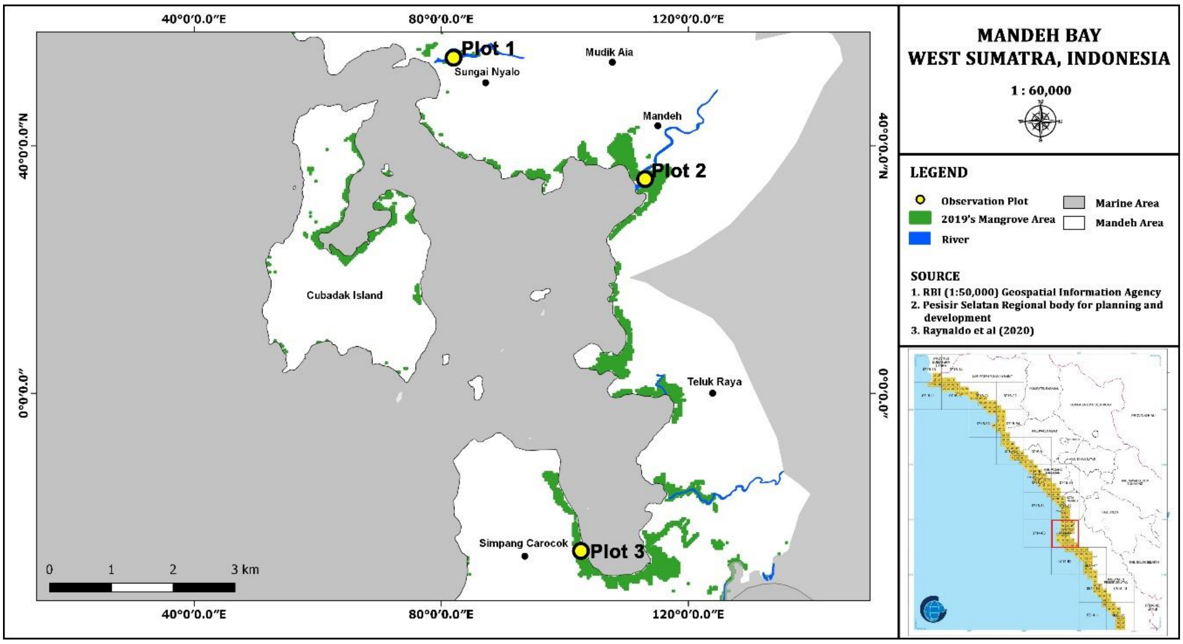

Figure 1. Mangrove distribution in Mandeh Bay, West Sumatra.

Estimation of biomass and carbon stock. Calculation of biomass was conducted through allometric equations (Table 1). In the selected area, a 10x10 m plot was selected. Tree species, density and carbon stock of vegetation were recorded for each stand with the diameter at breast height (dbh) ≥4 cm. Carbon stocks were calculated through an approach of 46% of plant biomass consisting of stored carbon elements.

Table 1

Allometrics used in estimating biomass

Allometric	*Species*	*R^2*	*Source*
$Wtop = 0.251\ \rho D^{2.46}$	*Rhizophora apiculata*	0.98	Komiyama et al (2005)
$Wtop = 0.1848\ D^{2.3524}$	*Avicennia marina*	0.98	Dharmawan & Siregar (2008)

Note: Wtop - aboveground biomass (kg); D - diameter at breast height (cm); ρ - wood specific gravity (g cm^{-3})

Modeling and mapping the aboveground carbon stock. Several vegetation indices are used in the modeling of mangrove carbon stocks in the Mandeh area (Table 2). The selected vegetation index was analyzed using the maximum value algorithm from three images of data in each period.

Table 2

Vegetation index used in the analysis

Vegetation indices	*Formulation*	*Source*
NDVI	(NIR - RED)/(NIR + RED)	Pearson & Miller (1972)
IM	(NIR – SWIR)/(NIR x SWIR) x 10000	Winarso & Purwanto (2014)
CMRI	(NDVI – NDWI)	Gupta et al (2018)
MMRI	(|MNDWI| - |NDVI|)/(|MNDWI| + |NDVI|)	Diniz et al (2019)
MDI	(NIR – SWIR-1)/SWIR-1	Wang et al (2018a, 2018b)
MDI2	(NIR – SWIR-2)/SWIR-2	Wang et al (2018a, 2018b)

Note: NDVI - Normalized Difference Vegetation Index; IM - Mangrove Index; CMRI - Combined Mangrove Recognition Index; MMRI - Modular Mangrove Recognition Index; MDI - Mangrove Discrimination Index; MD12-Mangrove Discrimination Index 2; NIR - Near Infrared (Band 4 at L5 (Landsat 5) and L7, Band 5 at L8); SWIR - Shortwave Infrared (Band 5 at L5 and L7, Band 6 at L8); Red - Red (Band 3 at L5 and L7, Band 4 at L8).

Modeling aboveground carbon stock was based on the regression equation between the vegetation index and the carbon stock value determined by the field data collection. The model is analyzed using linear, quadratic, exponential and power regression. The best model was chosen by the highest correlation value of the four regression models and the lowest deviation value. Deviation values were obtained by simple aggregate (SA) analysis, bias, mean deviation and root mean square error (RMSE) (Congalton & Green 2009).

Results and Discussion

Vegetation structure and biomass. The distribution of the mangrove trees based on the diameter class is presented in Figure 2. Mangrove tree density ranges from 200 to 10000 individuals per ha, and the dominant size was 1-5 cm diameter in all the study plots. The lowest density was found for trees with 20-25 cm diameter, with 200 trees per ha. The number of tree seedlings at Plot 3 (as shown in Figure 1) was larger than at other plots, indicating this area had good regeneration processes.

The results showed that only two species of mangroves were found, namely *Avicennia marina* and *Rhizophora apiculata*. The aboveground biomass of mangrove species found at the study site shows a large difference between the three observation plots. In plot 1, the highest biomass of carbon stock (AGB) (167.3 t ha^{-1}) was observed, and in plot 3, the lowest one (24.1 t ha^{-1}). In general, the species *R. apiculata* contributes with a 232.7 t ha^{-1} AGB, while the species *A. marina* contributes with 19 t ha^{-1} (Figure 3).

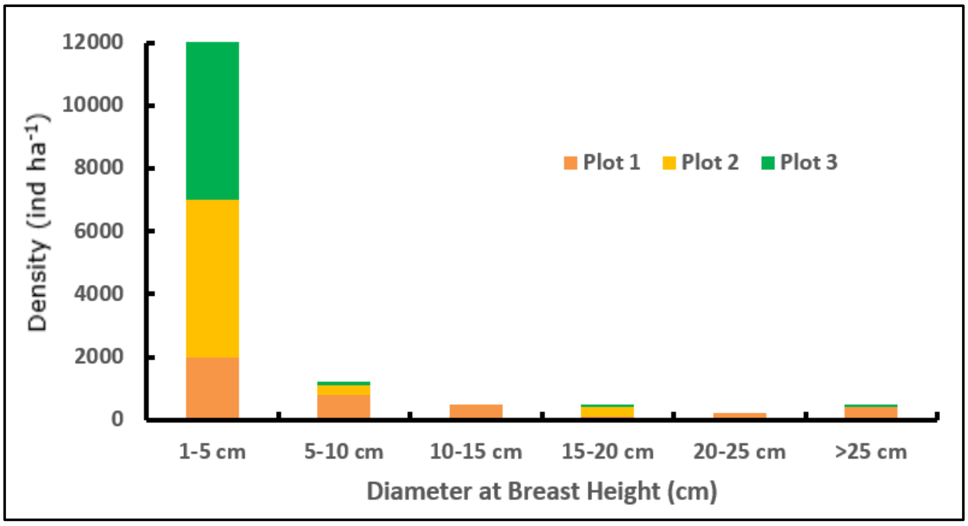

Figure 2. Mangrove density in Mandeh Bay, Indonesia, based on diameter class.

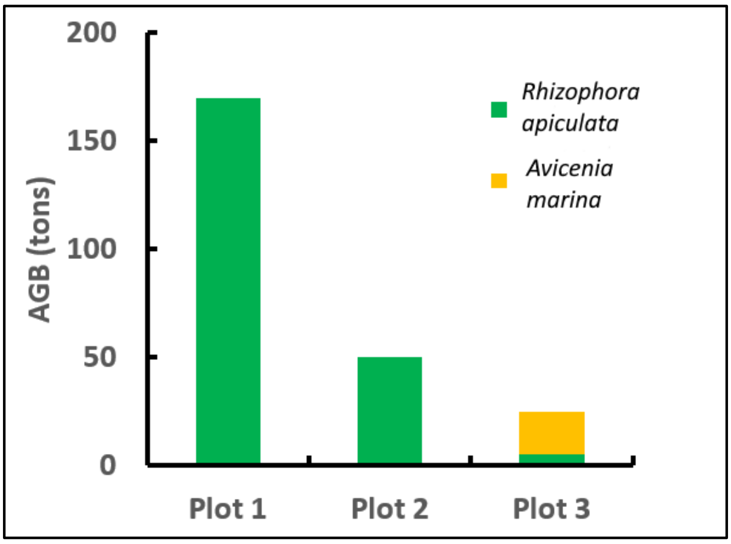

Figure 3. Distribution of mangrove stand biomass by species in Mandeh Bay, Indonesia; AGB - biomass of carbon stock.

Carbon stock model. The mangrove discrimination index is used in several related studies in mapping mangrove and non-mangrove vegetation. Through the use of specific band formulations with mangrove vegetation, some of these indices can separate mangrove and non-mangrove vegetation with accuracy of approximately 70%. In the study area, all indices used have a value gradient that can potentially correlate with the carbon stock value of mangrove vegetation as presented in Figure 4.

The coefficients values were variated, with a range of low to medium interrelationship values. IM and MDI1 correlate with the value of vegetation carbon stocks. Other indices used in this study indicate no correlation or have a low correlation to the value of carbon stocks (Table 3). Carbon stocks in the Mandeh area are the lowest when compared to several locations (Table 4). Through the results of the modeling, the total carbon stock in all mangrove areas at the study location was 2178996 Mg C.

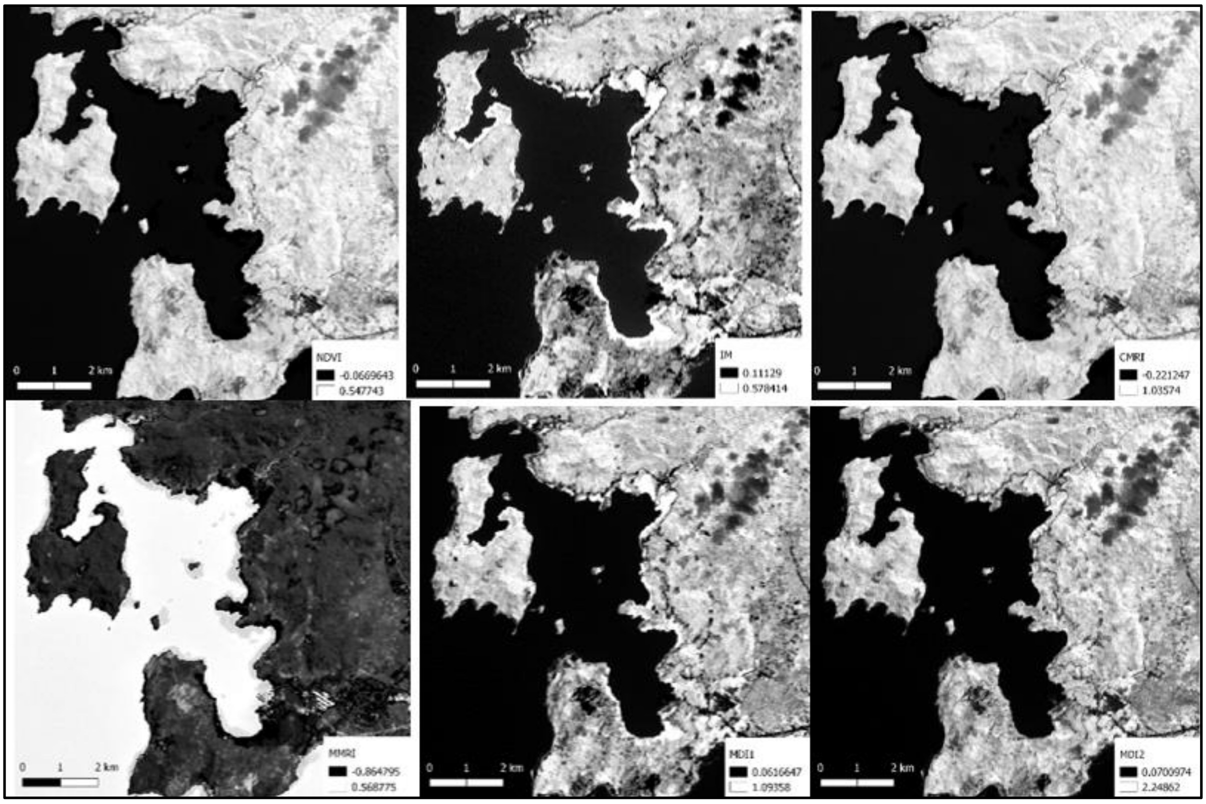

Figure 4. Visualization of the Mangrove Discrimination Index used in the study. NDVI - Normalized Difference Vegetation Index; IM - Index Mangrove; CMRI - Combined Mangrove Recognition Index; MMRI - Modular Mangrove Recognition Index; MDI - Mangrove Discrimination Index.

Carbon stock spatial distribution. Carbon stocks at the study site ranged from 0.58-5.38 Mg C per plot. The results found that the best mangrove index variable carbon stocks in the 2019 acquisition ranged from 0 to 8.44 Mg C. Furthermore, the distribution of organic carbon stored in mangrove vegetation shows variations, certain parts having potentially high carbon stocks (Figure 5).

Table 3

Carbon stock model validation

Variable	*Model*	R^2	*Bias*	*SA*	*RMSE*	*SR*
	Linear	0.070	0.00078	0.000772	86.8652	14.31102
NDVI	Logarithmic	0.079	0.00040	0.0004	86.93294	14.38821
	Power	0.089	-0.31778	-0.458	51.14495	30.3153
	Exponential	0.080	-0.30740	-0.43652	52.09681	25.52281
	Linear	0.548	0.00021	0.000204	80.77	42.71121
IM	Logarithmic	0.532	0.00049	0.000486	81.5062	39.34903
	Power	0.551	-0.20688	-0.25708	44.53594	25.51498
	Exponential	0.566	-0.20245	-0.25019	43.70462	25.17117
	Linear	0.082	0.00025	0.000251	86.96	14.41759
CMRI	Logarithmic	0.092	0.00084	0.000832	87.13666	14.46996
	Power	0.103	-0.31484	-0.45184	51.62045	30.34761
	Exponential	0.093	-0.31467	-0.45149	51.51925	25.95252
	Linear	0.101	0.00022	0.00022	92.54	11.14739
MMRI	Logarithmic	-	-	-	-	-
	Power	-	-	-	-	-
	Exponential	0.090	-0.31802	-0.45851	53.68357	21.13993
	Linear	0.245	0.00034	0.00034	87.95	16.63866
MDI1	Logarithmic	0.246	0.000	0.000	87.910	16.695
	Power	0.263	-0.279	-0.380	53.687	29.687
	Exponential	0.261	-0.24825	-0.3252	56.75948	25.82246
	Linear	0.101	0.00085	0.000843	87.25	14.54373
MDI2	Logarithmic	0.112	0.001	0.001	87.355	14.640
	Power	0.124	-0.312	-0.446	52.083	30.494
	Exponential	0.220	-0.32633	-0.4762	50.51615	26.63006

Note: NDVI - Normalized Difference Vegetation Index; IM - Mangrove Index; CMRI - Combined Mangrove Recognition Index; MMRI - Modular Mangrove Recognition Index; MDI - Mangrove Discrimination Index.

Table 4

Comparison of vegetation index models to estimate carbon stock in the mangrove area

Location	*Variable*	*Best Model*	R^2	*AGB (Mg ha^{-1})*
Kubu Raya, West Kalimantan[1]	NDVI (L8) and NDVI SPOT 5	$y = 0.000234e^{20x}$ $y = 0.36 + 25.5x^2$	0.77 0.49	20-46
Matang Mangroves, Peninsular Malaysia[2]	NDVI (L8)	$y = 392.61x - 23.93$	0.787	1.01–263.65
Perancak Estuary, Bali[3]	NDVI (L5)	$y = 305.9x^{4.864}$	-	22.18
Segara Anakan and Alas Purwo, Cilacap[4]	Tree Height*NDVI (L8)	$y = 448.09x+800.09$	0.89	-
Benoa Bay, Bali[5]	mRE-SR Worldview-2	Quadratic	0.85	90.18
Karimunjawa Island[6]	EVI1 ALOS AVNIR-2	$y = -376.29x-75.146$	0.688	216.4
Mandeh Bay, West Sumatra[7]	IM	$Y = 0.000005582e^{15.829x}$	0.566	8.32±0.08

Note: NDVI - Normalized Difference Vegetation Index; IM - Mangrove Index; sources: 1 - Yusandi et al 2018; 2 - Hamdan et al 2013; 3 - Hastuti et al 2017; 4 - Winarso et al 2015; 5 - Candra et al 2016; 6 - Wicaksono et al 2016; 7 - present study.

The contribution of biomass and carbon stocks in the three plots from the Mandeh area is determined by the distribution of individual densities in each diameter class. The highest biomass was found in plot 1, with the dominant distribution of tree diameter classes (>10 cm dbh) (Figure 2). Plot 3 had the least contribution of biomass, because the mangrove stands were dominated by seedlings.

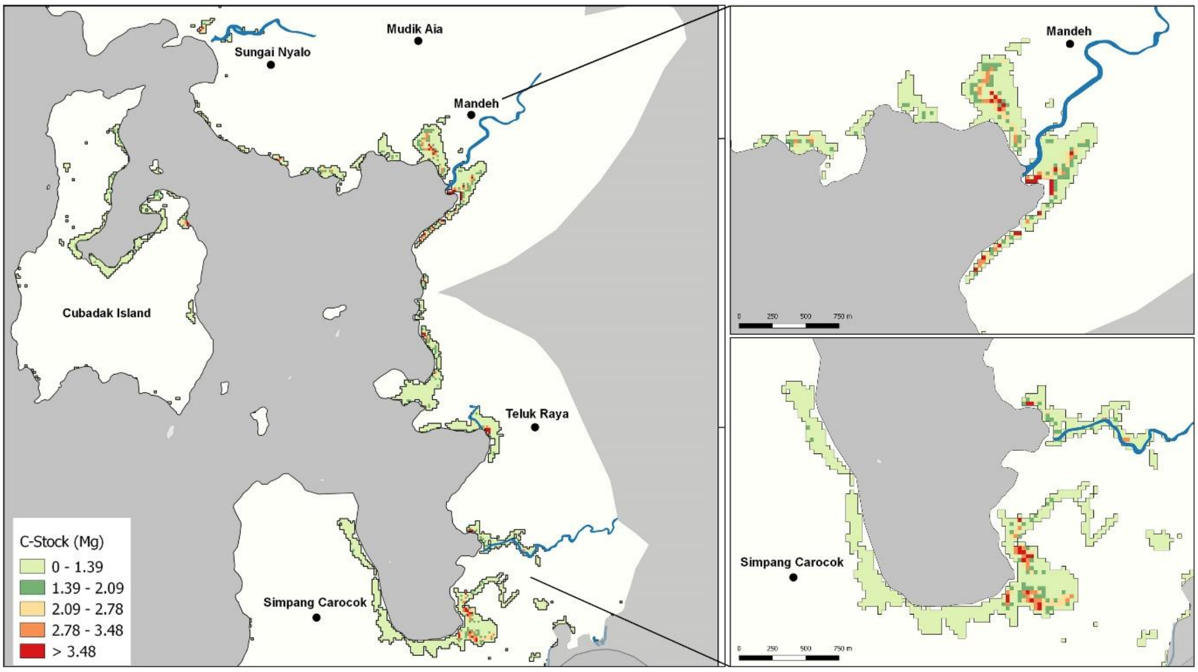

Figure 5. Spatial distribution of carbon stocks in Mandeh Bay.

Through validation, the best model was the mangrove index variable by Winarso & Purwanto (2014), using exponential regression (Table 3). The exponential model is chosen based on the value of the regression coefficient, simple aggregate, and RMSE, and has the lowest average bias and deviation values. The IM variable that had a high regression coefficient and the lowest error was used in mapping carbon stocks at the site.

The use of vegetation index in carbon stock modeling has been done before. Imran & Ahmed (2018) examined the potential of vegetation index with Landsat 8 imagery as a variable to estimate forest biomass. Some vegetation indices used have a positive correlation with forest biomass, with a range of R^2 values between 0.23-0.68. In mapping the carbon stocks of mangrove areas, vegetation indexes are also used as variables (Table 4). NDVI can be used in a variety of vegetation models with a fairly high regression coefficient, but in this study, the NDVI model was not appropriate because of the vegetation characteristics in the Mandeh area. Through field data collection and interpretation of satellite imagery, mangrove vegetation in the Mandeh area is known to be dominated by saplings with a diameter distribution of 1-5 cm and with very close distances between individuals. NDVI is highly correlated with canopy density (Hendrawan et al 2018), the dense distribution of vegetation and canopy causing red wave absorption by high chlorophyll, so that the NDVI value in the detected image is high, resembling the condition of vegetation dominated by dense canopy trees. Therefore, determining the model with NDVI variables is not appropriate for use in Mandeh locations.

The mangrove community in the Mandeh area is included in the young category, with the predominance of saplings in almost the entire area. However, the carbon potential at this location is very large for the next few years due to the very dense vegetation distribution. From the results, the area with a high mangrove index and carbon stock is not only a result of the presence of mangrove vegetation, but it is also due to substrate factors, because the NIR and SWIR bands used in the index are sensitive to substrates and water (National Institute of Aeronautics and Space 2015). While factors affecting vegetation biomass besides canopy width and tree density are easily captured by images, trunk diameter and tree height are also very influential.

Several points have a high potential of carbon stocks, such as the village of Mandeh, with variations in the distribution carbon stocks. Simpang Carocok village (Plot 3) also has potential like Mandeh village. This area has high potential to become a protected area, because mangrove areas on the west side are difficult to reach by land, so there is minimal disruption to the growth and colonization of mangroves. Based on the mangrove density value, the contribution of stands with dbh >10 cm (trees) is very small and categorized as low (Wicaksono et al 2016). However, stands with diameter <10 cm have a good ability of regeneration. The existence of approximately 260 ha of mangrove forests (Raynaldo et al 2020) and coral reefs along the coastal area can support marine habitats and fishing activities in Mandeh Bay.

Many studies have shown a strong relationship between the presence of mangroves and fish catch as well as shrimp catch, which are influenced by the relative abundance of mangroves in an area (Manson et al 2005; Meynecke et al 2007; Nagelkerken et al 2008). Thus, the importance of mangrove forest habitats for aquatic life is clear. Because the function of mangrove forests as drivers of nearshore fishery production, conservation efforts are needed in order to increase sustainable fisheries products. Mangrove forest conservation should involve local communities and the government, because they have local wisdom that has been tested for a long time in preserving mangrove forests.

Conclusions. The best model used in mapping the distribution of mangroves in the Mandeh Bay is the exponential model of the Winarso and Purwanto's Mangrove Index, with formulation of $Y = 0.000005582e^{15.829x}$ (R^2=0.566, RMSE=43.71%). Total mangrove Aboveground Carbon Stock in Mandeh Bay was 2178996 Mg C or 8.32±0.08 Mg ha^{-1}. Based on the results of potential carbon stock found, mangrove forest areas that should be protected can be mapped.

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Authors:
Erizal Mukhtar, Department of Biology, Faculty of Mathematics and Natural Sciences, Andalas University, Padang 25163, West Sumatra, Indonesia, e-mail: erizalmukhtar@sci.unand.ac.id
Adityo Raynaldo, Department of Marine Sciences, OSO University, Pontianak 78113, West Kalimantan, Indonesia, e-mail: adityoraynaldo@gmail.com
Wilson Novarino, Department of Biology, Faculty of Mathematics and Natural Sciences, Andalas University, Padang 25163, West Sumatra, Indonesia, e-mail: wilsonnovarino@sci.unand.ac.id

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