Mangrove vulnerability index and carbon algorithm using Sentinel-2A satellite data at Kemujan Island, Karimunjawa Islands, Indonesia

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Abstract. Mangroves are important for the environmental sustainability, contributing to the global warming control, but they remain highly vulnerable under the pressures of the anthropogenic activities. Information for mangrove carbon monitoring, such as mangrove coverage area with accurate spatial data, is urgently needed. The aim of the current research was to develop a mangrove carbon algorithm based on field and Sentinel-2A data, and a vulnerability index of mangrove ecosystems at Kemujan Island. Mangrove density was in the range of 1,021 and 2,829 ind ha^{-1}. Mangrove sediment texture was dominated by sandy-clay-loam. The sediment organic matter content was of 0.4-24.4%, the sediment nitrate content was of 0.7702-4.4596 mg/L and the sediment phosphate content was of 0.0201-0.6354 mg L^{-1}. The redox potential of sediment was of 134-332 mV. The highest carbon absorption was measured in *Rhizophora apiculata* (49.681 ton C ha^{-1}). Carbon algorithm of *R. stylosa* was the best, according to the equation: mangrove carbon = 46.448 x (Band 4/Band 3)^2 - 83.421 x (Band 4/Band 3) + 37.334, with the highest determination coefficient R^2=0.9972 and a root-mean-square error (RMSE) of 0.1378. The mangrove vulnerability index was found in the low to moderate category.
Key Words: coastal ecosystem, biotic, abiotic, management, carbon algorithm.

Introduction. Mangrove forests have important environmental functions for the associated organisms. Maintaining the stability of the coastal ecosystem provides regulating services such as protection, simbiotic functions and carbon storage. Mangrove forests have a remarkable carbon-dioxide absorbtion capacity, reducing the global warming. According to Rospita et al (2017), mangrove ecosystems are unique and play an important role for the environment and socio-economic functions. Kemujan Island, one of the Karimunjawa islands, has extensive mangrove forests. The mangrove forests cover an area of 222.20 ha. Kemujan Island has three sub areas namely Legon Besar, Legon Tengah and Legon Pinggir. The mangrove zones regroup 44 species of trees. As stated by Cahyaningrum et al (2014), Kemujan Island is one of the largest mangrove forests areas in Karimunjawa. The island is divided between the mangrove forest and the community setlements.

The main Kemujan Island mangroves issues are deforestations and human activities causing land use change. In the early years of the 21st Century, approximately 15.27 ha of mangrove forests had been converted into shrimp ponds. These issues increase the mangrove forests vulnerability (Suryanti et al 2011). Thus, spatial information on ecosystem variables, species distribution, distribution of carbon biomass and mangroves vulnerability is needed in maintaining the mangrove forests sustainability. The current research focused on developing a carbon algorithm based on field and Sentinel-2A satellite data and on assessing the mangrove vulnerability, at Kemujan Island, Karimunjawa Islands. The study results can be used for maintaining and managing the mangrove forests in tropical zones.

Material and Method

The experimental research was located at Kemujan Island, Karimunjawa Islands and was conducted between September-October 2019, consisting of 14 sampling stations distributed along the coast of Kemujan Island. At each station line transects were applied perpendicularly on the coast, towards the upland. The distance between transect sampling points was of 25-30 m as presented in Figure 1.

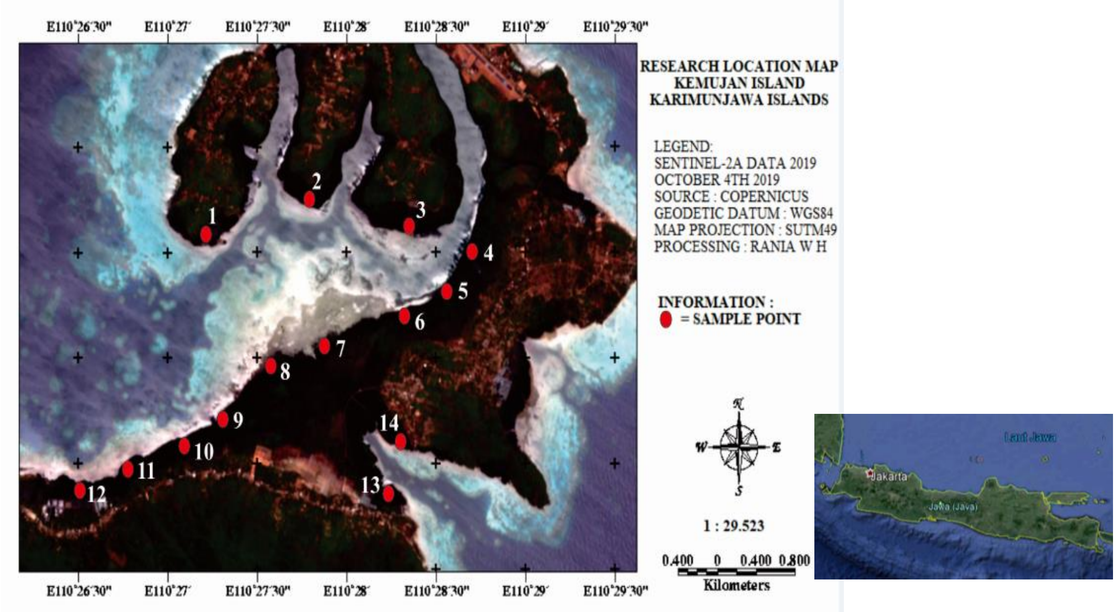

Figure 1. Research location and sampling point at Kemujan island.

Distinction was made between biotic and abiotic factors in the measurements of the ecosystem variables. Biotic factor was related to the calculation of mangrove density, recruitment and logging. The density of mangrove vegetation was calculated by using the Point Centered Quarter method (PCQ) according to Susiana (2011). A line transect determined the central points. A virtual quadrant was then created at the central point. Collected data included mangrove species identification, coordinate points and tree trunk diameters. Observations were carried out at all four parts of the quadrant. Abiotic variable data were collected through analysis of sediments, following analytical determinations: carbon biomass by non destructive method allometric equation (Table 1) and carbon conversion, where the conversion equation was carbon=0.50 biomass (Hartoko et al 2015); sediment texture, by the glass-tube setlement method (Buchanan 1984); salinity, by syringe methods (Aini et al 2016); nitrate and phosphate contents, based on SNI 06-6989-31-2005; calculation of the sediment redox potential, using an Eh-meter type 42D SN-730692; sediment organic material, using the loss on ignition method (Allen et al 1974).

Table 1

Mangrove tree allometric equation (Suryono et al 2018)

Species	*Allometric*
Avicennia alba	$B=0.079211 \times D^{2.470895}$
Avicennia marina	$B=0.1848 \times D^{2.3524}$
Rhizophora apiculata	$B=0.43 \times D^{2.63}$
Rhizophora mucronata	$B=0.1466 \times D^{2.3136}$
Sonneratia alba	$B=0.3841 \times p \times D^{2.101}$
Bruguiera gymnorrhiza	$B=0.0754 \times p \times D^{2.505}$
Ceriops tagal	$B=0.251 \times p \times D^{2.46}$
Xylocarpus granatum	$B=0.1832 \times D^{2.21}$

B-biomass; p-wood density; D-diameter at breast high (DBH).

Configuration of the algorithm of mangrove carbon biomass used both the field measured carbon and Sentinel-2A satellite data. Distribution maps were expected to help identifying the species spatial distribution in order to estimate the ability of mangrove species to preserve the environment, by determining their capacity of carbon-dioxide absorption from the atmosphere. Satellite data processing used ErMapper 7.0 software functions, such as: downloading images, cropping images for sampling location, digital numbers (DN) sampling from several bands, according to the field coordinates, for the algorithm configuration. These bands were: band 1, for coastal aerosol. having a wavelength of 0.443 μm; band 2, showing the blue spectrum and having a wavelength of 0.490 μm; band 3, showing the green spectrum and having a wavelength of 0.560 μm, and band 4, showing red spectrum and vegetation, with a wavelength of 0.665 μm. The algorithm was based on the polynomial regression between the combination of two bands and the field measured carbon. The combination of bands might be either a sum or a thresholding or an average or a ratio of two bands. The algorithm accuracy was tested using RMSE calculations. According to Ratnasari & Bangun (2017), a geometric accuracy correction was needed, based on the differences of X and Y regression values, where X is the field actual data and Y is the result of the satellite data algorithms.

Mangrove forest vulnerability index (MVI) determination was based on the method presented by Ellison (2015). This method was derived from the Coastal Vulnerability Index (CVI) method (Ellison 2015; Yunus et al 2017) and contextualized. The MVI method was used to determine the level of vulnerability of a coastal area in terms of response to environmental, ecological and social factors, grouped into three index variables: exposure, sensitivity and adaptive capacity. Yunus et al (2017) explained that the index of exposure shows the total pressure received by an area, such as anthropogenic pressures. The sensitivity index refers to the original characteristics or conditions of the natural environment. The adaptive capacity shows the responses of species or ecosystems, also suggesting management actions that can reduce the vulnerability. Values of each variable affecting the mangrove forests were first allocated to one of the five sensitivity ranks. The ranks were based on literature guidance (Juwita et al 2015; Tiryana et al 2016; Isman 2016; Wibisana 2004; Ellison 2015), where class 1 corresponds to the lowest vulnerability and class 5 to the highest. Ranks of each variable was presented in Table 2.

Table 2

Ranks of each variables

Rank	*1*	*2*	*3*	*4*	*5*
Mangrove's density	>1500	1000-1500	500-1000	100-500	<100
Carbon	156-253	97-156	62-97	35-62	<35
Sediment	Silt	Sandy silt	Sand	Sandy gravel	Gravel
Organic matter	27-35	17-27	10-17	7-10	3.5-7
Redox	>300 mV	300 mV	0	-200 mV	<-200 mV
Salinity	>13.75	9.75-13.75	6.875-9.75	4-6.875	<4
Nitrate	10.12-11.25	1.13-10.12	0.90-1.13	0.23-0.90	<0.23
Phosphate	0.81-1	0.61-0.8	0.41-0.6	0.21-0.4	0-0.2
Recruitment density	100%	75%	50%	25%	0%
Mortality	<4%	4-10%	10-20%	20-30%	>30%
Elevation	>60 cm	50-60 cm	30-50 cm	20-30 cm	<20 cm
Coral reef density	100%	75%	50%	25%	0%
Seagrass density	100%	75%	50%	25%	0%

Then variables were measured and the quantitative and qualitative data were generated. Qualitative data described the way the environmental conditions affect the mangrove species habitat, while to the quantitative data, mostly bioindicators, there were assigned vulnerability levels according to the five categories. Vulnerability at each experimental station was calculated as a mean: the sum of each variable ranking, divided by the number of variables:

Vulnerability rank=Total ranking for all the variables/Number of variables

The vulnerability classification of mangrove forests is presented in Table 3.

Table 3

Mangrove vulnerability index

Vulnerability	*Class*
Very low	1
Low	2
Moderate	3
High	4
Very high	5

Results and Discussion

Observations of enviromental variables include biotic and abiotic factors. The results of biotic factors as presented in Table 4. The highest density was recorded at station 7, with a density value of 2,829 ind h^{-1}, while the lowest density was recorded at station 5, with a density value of 1,021 ind h^{-1}. Density values were categorized from moderate to good. Susiana (2011) showed that, based on the Decree 201/2004 of the Minister of Environment, a high mangrove density value is greater than 1,500 trees ha^{-1}, a moderate density is between 1,000 and 1500 trees ha^{-1}, and a low density is lower than 1,000 trees ha^{-1}. Local community has to support and make efforts to preserve mangrove forests, in particular by ceasing ilegal logging. The absence of ilegal logging activities correlates with an increased absorption of carbon dioxide from the atmosphere. Senoaji & Muhammad (2016) highlighted that local community support is imperative in order to maintain the mangrove ecosystem.

Table 4

Biotic ecosystem variables

Station	*Density(ind h^{-1})*	*Recruitment*	*Mortality*
1	1,722	100%	>30% (logging traces)
2	1,514	0%	<4%
3	2,311	0%	<4%
4	1,975	100%	>30% (logging traces)
5	1,021	100%	>30% (logging traces)
6	1,600	100%	<4%
7	2,829	100%	<4%
8	1,104	100%	<4%
9	1,266	100%	<4%
10	2,427	100%	<4%
11	1,468	100%	<4%
12	1,285	100%	<4%
13	1,765	100%	>30% (logging traces)
14	2,427	100%	>30% (logging traces)

Logging traces-are indicated by evidences, such as pieces of wood, without current logging activity.

The results concerning abiotic factors are presented in Table 5.

Table 5

Abiotic ecosystem variables

St	*Points*	*ST*	*Sal*	*LE*	*OM*	*N*	*P*	*RP*	*CR*	*S*
1	1	SS	40	30	0.6	1.80	0.42	150	v	v
	2	SCL	38		0.8					
2	1	SC	43	5	2	3.16	0.05	297	v	v
	2	SCL	40		2.4					
3	1	SCL	49	5	12.2	4.46	0.32	122	v	v
	2	S	47		16.6					
4	1	S	40	9	16.2	3.71	0.02	150	v	v
	2	SC	37		19					
5	1	SCL	40	7	2.4	4.04	0.11	171	v	v
	2	SCL	38		20.4					
6	1	SCL	45	7	0.4	1.94	0.08	260	v	v
	2	SCL	44		1					
7	1	SC	45	3	0.4	0.77	0.17	286	v	v
	2	SCL	42		0.6					
8	1	SCL	41	7	0.4	2.14	0.10	134	v	v
	2	SC	41		0.6					
9	1	SC	38	10	4.8	3.44	0.06	297	v	-
	2	SCL	38		15.2					
10	1	S	42	36	5	4.34	0.25	261	v	-
	2	S	40		16.4					
11	1	C	42	25	9.6	3.22	0.23	166	v	v
	2	SC	40		16.6					
12	1	C	40	12	9.4	3.05	0.19	299	v	v
	2	S	37		24.4					
13	1	SCL	39	4	2	3.06	0.64	332	v	-
	2	S	38		7.4					
14	1	SS	37	5	0.6	0.98	0.23	280	v	-
	2	SCL	36		10.6					

St-station; ST-sediment texture; SS-sandstone; SCL-sandy clay loam; SC-sandy clay; S-sand; C-clay; Sal-salinity; LE-land elevation; OM-organic material; N-nitrate; P-phosphate; RP-redox potential; CF-coral reef; S-seagrass; (v)-present.

The dominant sediment texture at the study site was the sandy clay loam. Yulma et al (2019) stated that substrates in the downstream area or river estuarine tends have a finer texture and are dominated by mud or clay. Sediment salinity ranged from 37 to 49‰. Variation of salinity will affect the growth and zoning of mangrove tree species. According to Matatula et al (2019), the factors affecting mangrove ecosystems in coastal areas include sea tides, rainfall, waves and also salinity. Mangrove area elevation ranges from 3 to 36 cm. Research locations areas are vulnerable to the influence of sea water. Hamuna et al (2018) group mangroves vulnerability, related to land elevation, as follows: very vulnerable at 0-5 m, vulnerable at 5-10 m, of moderate vulnerability at 10-20 m, less vulnerable at 20-30 m is and not vulnerable at an elevation of more than 30 m. Sediment organic matter ranged from 0.4 to 24.4%. Low organic matter at some stations is due to a location directly adjacent to sea water. Saru et al (2017) stated that coastal areas at the border of seawater tend to have lower or fluctuating organic matter values, due to the influence of waves and tides. The nitrate concentration in sediments from the 14 sampling locations ranged between 0.77 and 4.46 mg L^{-1} and phosphates concentration ranged from 0.02 to 0.64 mg L^{-1}. Dewi et al (2017) suggested that nutrients concentration variation in sediments can be influenced by several environmental factors: nitrate concentrations are usually higher in coastal areas and lower at inland; phosphate concentrations depend on the amount of organic residues around the sampling location. Both nitrate and phosphate concentrations will be higher in the mud and clay fractions. Substrates with a high sand fraction are less likely to bind nutrients, due to larger sediment particles size.

The sediment redox potential values measured at the study site ranged from 134 to 332 mV. Sediments can originate either from the transition zone or from the oxidation zone. Variations of the redox potential can also be determined by environmental factors. As stated by Syahrial et al (2018), the sediments redox potential is an environmental conditions indicator. Factors affecting the redox potential are rainfall, tides, location, depth of sampling and sediment texture. Redox value will decrease with the decrease of the distance to the estuary or coastal area. The natural presence of many mangrove seedlings, at almost all stations, indicated that mangrove trees breed and grow in good environmental conditions and that parent trees are able to recruit seedlings for the species survival (Istomo & Mia 2018). The preservation of mangrove forests depends on the species rejuvenation, fact denoted by the presence of seedlings. Ecosystem's health status is demonstrated by the presence of bioindicators, such as coral reef and seagrass near the observation stations. Dewi & Sigit (2015) suggested that the co-existence of mangrove and seagrass is influenced by several factor: sediment texture, depth, currents and strong waves. Strong currents over the seagrass beds can displace the sediments with seagrass roots and eventually uproot and sweep seagrass towards the mainland.

Spatial analysis. The highest field mangrove carbon can be found in *Rhizophora apiculata* with a value of 49.681 ton C ha^{-1}. The lowest field mangrove carbon was found in *Lumnitzera racemosa* with a value of 0.033 ton C ha^{-1}. Following the analysis of the polynomial regression between the field mangrove carbon values and the digital numbers obtained from Sentinel-2A satellite data, the mangrove carbon algorithm of each species could be identified, as presented in Table 6.

The accuracy of the algorithms had been tested using RMSE and the result for all algorithms ranged between 0.1378 and 0.2. Parmadi & Bangun (2016) explained that a RMSE value ≤1 and close to 0 indicates a better accuracy. The highest correlation coefficient (r) was of 0.998 for the *R. stylosa* mangrove species found in in the studied area (Table 6).

Table 6

Mangrove carbon algorithm

Species	*Algorithms*	R^2
Ra	$C = 26.665 \times (B2/B4)^2 - 84.389 \times (B2/B4) + 67.308$	0.5245
Rm	$C = 4E\text{-}05 \times ((B4+B3)/2)^2 - 0.068 \times ((B4+B3)/2) + 26.447$	0.714
Rs	$C = 46.488 \times (B4/B3)^2 - 83.421 \times (B4/B3) + 37.342$	0.9972*
Am	$C = -6E\text{-}05 \times (B1\text{-}B2)^2 - 0.047 \times (B1\text{-}B2) + 8.0741$	0.5266
Ct	$C = 0.0014 \times (B2\text{-}B3)^2 - 0.31 \times (B2\text{-}B3) + 17.143$	0.7106
Sa	$C = 0.0001 \times (B1\text{-}B3)^2 - 0.0862 \times (B1\text{-}B3) + 17.211$	0.5433
Bc	$C = 0.0024 \times (B4\text{-}B3)^2 - 1.2479 \times (B4\text{-}B3) + 158.94$	0.8849
Bg	$C = 0.0002 \times ((B3+B2)/2)^2 - 0.3002 \times ((B3+B2)/2) + 135.11$	0.7146

Am-*Avicennia marina*; Ra-*Rhizophora apiculata*; Rm-*Rhizophora mucronata*; Rs-*Rhizophora stylosa*; Bc-*Bruguiera cylindrica*; Bg-*Bruguiera gymnorrhiza*; Sa-*Sonneratia alba*; Ct-*Ceriops tagal*; C-carbon; B1-band 1; B2-band 2; B3-band 3; B4-band 4; *-the highest R^2.

Carbon is stored in all parts of mangrove trees, meaning that the storage capacity of the tree depends on its size. Hartoko et al (2015) suggested that the factors determining the mangrove carbon sequestration and storage variability are: the form, type and density of the mangrove trees. Values and distribution of the mangrove carbon are visible on the colour scale. As explained by (Hartoko et al 2015; Kawamuna et al 2017; Hartoko et al 2019), the use of a correct satellite spectral band and wave length will give the best algorithm, by using a spectral band combination through the methods of: band averaging, rationing and thresholding. The color spectral value can vary according to the vegetation cover and to the intensity of the radiation reflected. The carbon distribution at the study site, based on the algorithm with the highest determination coefficient (R^2), of 0.9972, with a corelation coefficient (r) of 0.998, is presented in the Figures 2, 3 and 4.

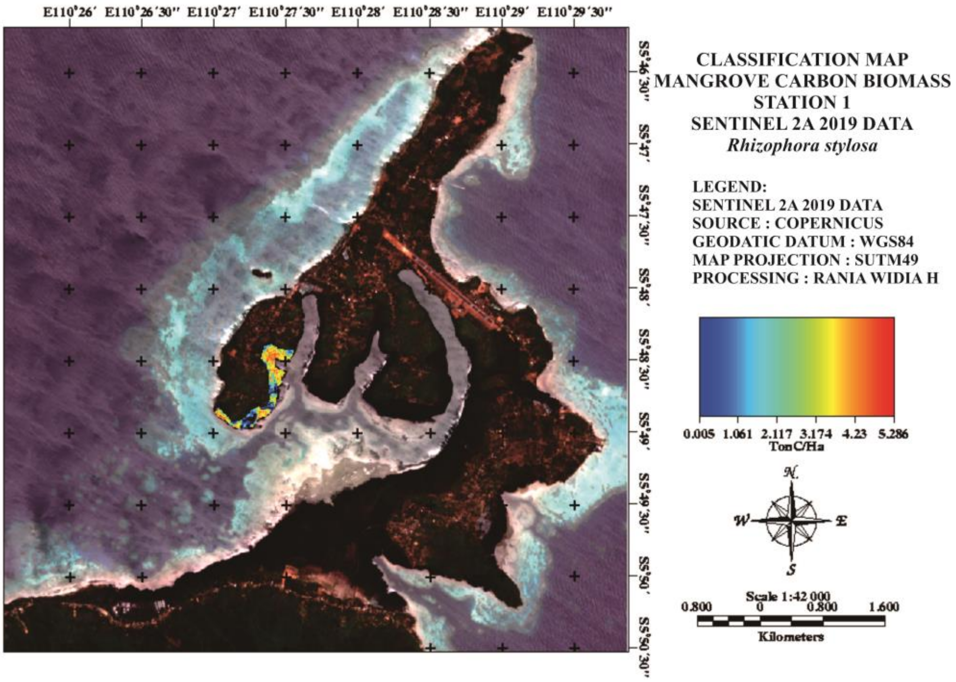

Figure 2. Mangrove carbon of *Rhizophora stylosa* at station 1 Kemujan Island.

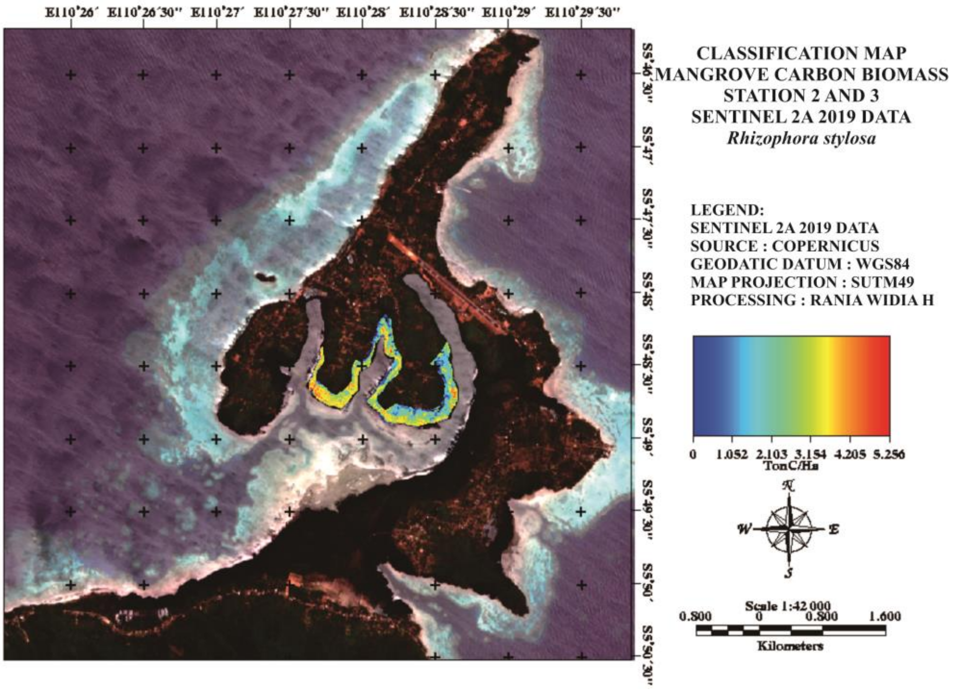

Figure 3. Mangrove carbon of *Rhizophora stylosa* at station 2 and 3 Kemujan Island.

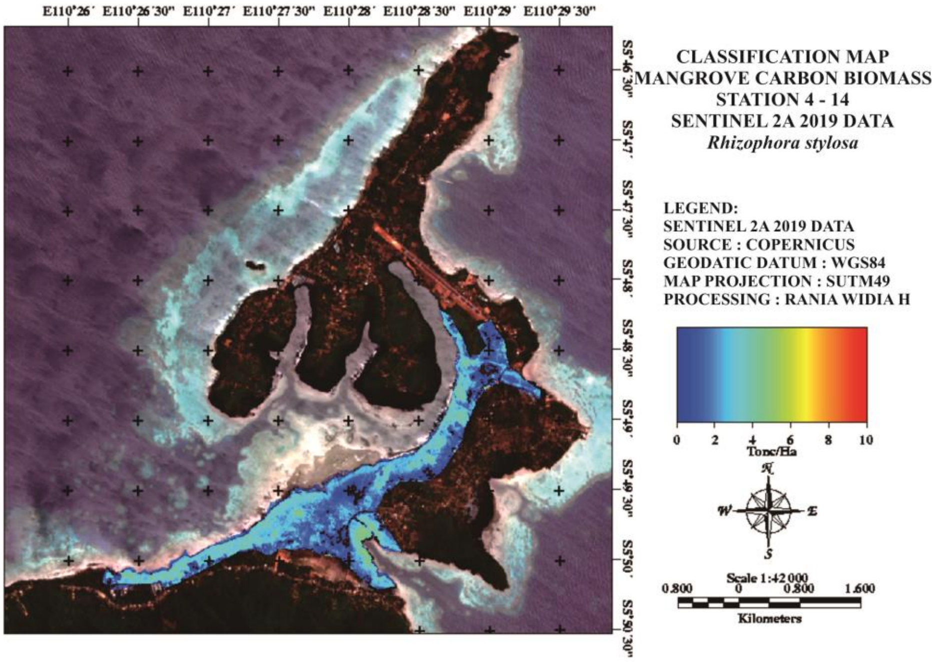

Figure 4. Mangrove carbon of *Rhizophora stylosa* at station 4-14 Kemujan Island.

The resulted mangrove vulnerability index values ranged from 2.38 to 2.92, meaning that at all the stations of the study site mangroves were categorized in the moderate level of MVI. The spatial distribution of the MVI values is presented in Figure 5, indicating that a continuous mangrove ecosystem monitoring and management are required. Ellison (2015) stated that values of MVI between 1 and 2 indicate that mangrove areas have a good environmental resilience. MVI values above 2 and up to 4 indicate that mangrove areas are in a moderate vulnerability category. MVI values above 4 indicate a high vulnerability level and require immediate rehabilitation and ecosystem management actions.

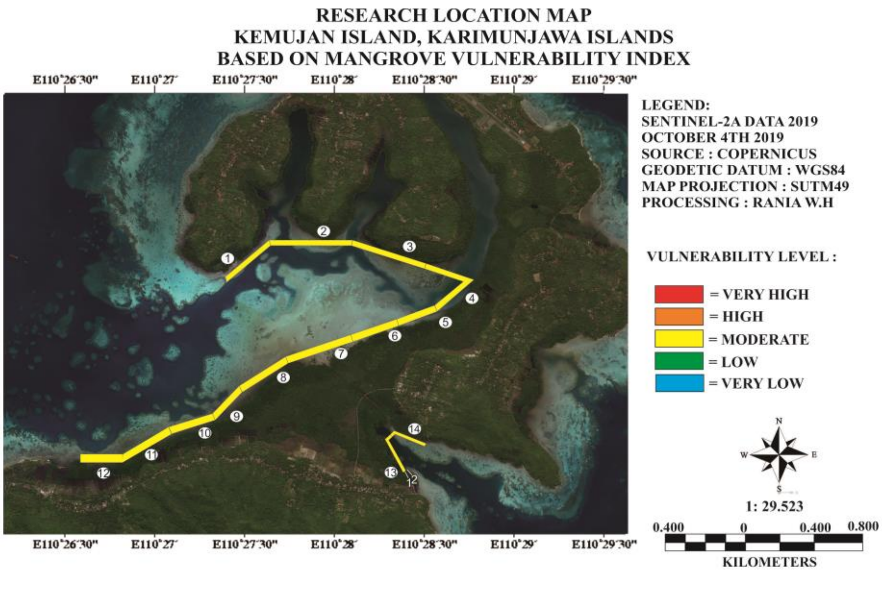

Figure 5. Mangrove vulnerability index at Kemujan Island.

Conclusions. Data based on field and Sentinel-2A satellite observations were used to develop a carbon algorithm for each mangrove species. The regression equation between the field carbon and the satellite data for *R. stylosa* had the highest determination coefficient (R^2) value (0.9972), indicating that it is the best algorithm. The highest field mangrove carbon was determined for *R. apiculata*, with a value of 49.681 ton C ha^{-1}. Mangrove forests vulnerability assessment using the MVI method indicated a medium vulnerability level of the study area, requiring intensive management.

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