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RESEARCH ARTICLE

Multitemporal Analysis of Aboveground Carbon Stock of Seagrass Meadows using Sentinel-2 in the Coastal Area of Bontang City in 2020-2024

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Abstract

Seagrass is one of the ecosystems that absorbs large amounts of carbon in the blue carbon ecosystem. This ecosystem also has many benefits, such as becoming the habitat for fish and improving water quality. However, there is degradation of the seagrass ecosystem that requires annual carbon inventory with Sentinel-2 which covers benthic habitat areas and has high spatial resolution. This study aims to map changes in the area and distribution of seagrass meadows, as well as to map and estimate changes in aboveground carbon stocks (AGC) of seagrass meadows in part of the coast of Bontang City, East Kalimantan annually with a range of 2020-2024. The methods used in this study include integration with field data, benthic habitat classification and AGC regression with the Random Forest (RF) algorithm, accuracy testing, and multitemporal mapping to detect changes. The results of this study indicate that the benthic habitat class is dominated by seagrass which remains from 2020 to 2024 covering an area of 2643.92 hectares and the area of seagrass tends to decrease from 2808.14 hectares to 2745.94 hectares. The benthic habitat classification used to classify the seagrass area has an Overall Accuracy of 65.9%. Meanwhile, the total estimation of Seagrass AGC decreased from 287.12 tons of carbon in 2020 to 265.6 tons in 2024 of carbon from an area of 3118.6 hectares. The model from the regression results was tested for accuracy with an RMSE of 2.09 gC/m^2, R^2 of 0.65, and a Plot Goodness of Fit of 1:1 which explains that the estimated AGC sample is positively correlated with the field AGC sample.

Keywords: Seagrass mapping, Sentinel-2, time series, carbon stock

1. Introduction

1.1 Background

Blue carbon ecosystems, which is coastal and marine ecosystems, can absorb large amounts of carbon and help to overcome the climate change. These ecosystems consist of seagrass, mangroves, and coral reefs that are spread throughout Indonesia (Fauzi et al., 2021). The seagrass ecosystem is one of the ecosystems that stores the best carbon because it undergoes a good absorption process through photosynthesis, carbon storage in the seagrass' body, then stored in the sediment at the bottom of the ground (Ansari et al., 2020). The large potential of seagrass in Indonesia is also supported by the area of seagrass meadows of 8,812.9 km^2 which makes Indonesia the second country with the largest seagrass meadows in Southeast Asia (Fortes et al., 2018). Seagrass ecosystems are also important for coastal ecosystems globally because they provide many benefits, such as being a habitat for fish and invertebrates, supporting food sources for local communities, and improving water quality (Rifai et al., 2023).

Although seagrass ecosystems have many benefits, there is degradation in seagrass ecosystems in Southeast Asia of 2.82% per year which produces carbon emissions of 1.65 to 2.08 Tg CO2 per year (Stankovic et al., 2021). This requires a carbon inventory to monitor changes in seagrass meadows and their carbon stocks. The Intergovernmental Panel on Climate Change (IPCC) also explains that carbon inventory requires annual monitoring of carbon changes (Wicaksono et al., 2022). Multitemporal analysis of satellite imagery in coastal areas can also help decision-making to reduce dangerous risks in coastal areas (Bergsma & Almar, 2020). Therefore, it is necessary to monitor seagrass carbon stocks in time series using remote sensing technology. This analysis can aim to monitor changes in seagrass through integration with previously conducted modelling (Lyons et al., 2013).

Seagrass carbon stocks can be estimated based on aboveground carbon or Above Ground Carbon (AGC) and belowground carbon or Below Ground Carbon (BGC), with AGC that can be recorded by satellite imagery. The carbon stock can be represented by a carbon stock map that can explain the dynamics of seagrass distribution temporally and spatially (Rais et al., 2023). The analysis can use Sentinel-2 imagery because it is freely accessible and covers areas almost all over the earth's surface, including for mapping seagrass and benthic habitats (Wicaksono et al., 2021a). This is due to its high spatial resolution, which is from 10 m meters to 60 meters depending on the channel. There are 13 channels on this satellite, such as visible, red edge, near infrared, and water vapor channels. This satellite has a temporal resolution of five days with the most recordings on the equator (Bergsma & Almar, 2020).

Sentinel-2 also has the main objective of observing changes temporally so that it is suitable for monitoring changes in seagrass (Wicaksono et al., 2021a).

One of the areas in Indonesia with seagrass potential for analysis is the coast of Bontang City, East Kalimantan. This city consists of 70.29% seawater and a coastline of 161.19 km (BPS Kota Bontang, 2024). This makes the city known for its fisheries and marine production, making it productive for its economic activities (Sudirman et al., 2023). This productivity can be seen from the vast seagrass meadows on the coast of Bontang City of 5.17 ha with five species, namely Enhalus acoroides, Thalassia hemprichii, Halophila minor, Cymodocea ratundata and Halodule pinifolia (Irawan et al., 2019). However, there is very little research on mapping seagrass meadows on part of the coast of Bontang City using remote sensing technology. Therefore, this data needs to be further analyzed by mapping seagrass meadows with Sentinel-2 on part of the coast of Bontang City annually to determine changes in the area and carbon stock of seagrass.

1.2 Study Area

Blue carbon ecosystems, which is coastal and marine ecosystems, can absorb large amounts of carbon and help to overcome the climate change. These ecosystems consist of seagrass, mangroves, and coral reefs that are spread throughout Indonesia (Fauzi et al., 2021). The seagrass ecosystem is one of the ecosystems that stores the best carbon because it undergoes a good absorption process through photosynthesis, carbon storage in the seagrass' body, then stored in the sediment at the bottom of the ground (Ansari et al., 2020). The large potential of seagrass in Indonesia is also supported by the area of seagrass meadows of 8,812.9 km^2 which makes Indonesia the second country with the largest seagrass meadows in Southeast Asia (Fortes et al., 2018). Seagrass ecosystems are also important for coastal ecosystems globally because they provide many benefits, such as being a habitat for fish and invertebrates, supporting food sources for local communities, and improving water quality (Rifai et al., 2023).

2. Material and Methods

2.1 Image Pre-Processing

Median mosaic images of Sentinel-2 Level 2A recorded in June-September 2020, 2021, 2022, 2023, and 2024 were downloaded using the Google Earth Engine (GEE) website. The median mosaic image is an image obtained from selecting the median value of all images that meet the requirements and have no spectral differences between several times (Li et al., 2019). The median mosaic image was chosen because it is a method often used to improve images with cloud cover (Phan et al., 2020). Five images were downloaded because the analysis carried out was a multitemporal analysis to analyze change detection

The images that had been downloaded from GEE were then corrected for sunglint. The sunglint effect is an effect on seawater that looks like bright spots that obscure information below the sea surface so that it is difficult to interpret and map the benthic habitat (Wicaksono, 2012). The correction can be done by creating a regression model between the visible and near infrared channels based on the variation of sunglint reflectance across the image scene (Wicaksono et al., 2022). The sunglint correction method used in this study is the method developed by Hedley et al. (2005) which establishes a linear relationship between the NIR and visible channels with linear regression on pixel samples from the image (Hedley et al., 2005). The method is found in the following formula.

$$R_i' = R_i - b_i(R_{NIR} - Min_{NIR}) \quad (1)$$

where R_i' is the reflectance of the visible band that corrected by the sunglint correction, R_i is the reflectance of the visible band i, b_i is the slope of visible band regression. R_{NIR} is the reflectance of the NIR band, and Min_{NIR} is the smallest pixel value on the NIR band that free from the sunglint effect.

2.2 Field Survey

Field data were obtained from the "Indonesia Seagrass Map: Framework and Implementation" activity, which is a collaboration between Universitas Gadjah Mada, BRIN, the Indonesian Ministry of Marine Affairs and Fisheries, the Geospatial Information Agency, and the University of Queensland Australia, and is a grant from The David and Lucile Packard Foundation. One of the locations of this activity is part of the coast of Bontang City on 2-10 August 2024 where data was taken on the percentage of benthic habitat cover for national seagrass mapping.

Field data were taken using the photo-transect method, which is taking photos of benthic habitats on the seabed in coastal areas following transect lines, which is on the Figure 1. Photo-transect is a method used to collect seabed cover information regarding the nature of seagrass that is spatially referenced, so that it is useful in mapping and validating the resulting map (Phinn et al., 2008). The photo-transect method begins by matching the time (hours, minutes, and seconds) on the underwater camera and GPS, so that the data can be integrated after the field survey activity. The GPS requires editing of the correct projection and datum, then tracking mode is carried out every few seconds. The GPS is then inserted into a dry bag so that it is not damaged if exposed to water. When the GPS and underwater camera settings are complete, the survey can be carried out by taking pictures at a height of about 1 m from the seabed using an underwater camera. The resulting photos are then processed in the CPCe software (Roelfsema & Phinn, 2009).

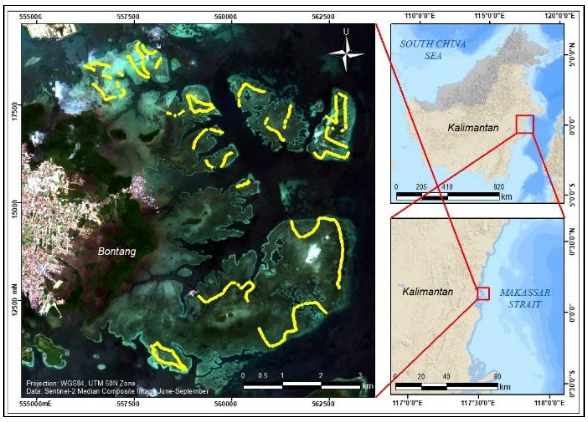

Fig 1. Transect of the Field Survey

2.3 Post-Survey Data Processing

The photo-transect obtained in the field survey is integrated to the Sentinel-2 images by combining the samples into one sample for every pixel in the images. This integration using the Create Fishnet tools on ArcMap 10.8, which made fishnet for every pixel in the satellite images, so the samples could be combined into one sample per pixel.

After that, the images are masked with a shapefile that covered the area of interest, which is the part of the Bontang city coastal area without including the area covered with clouds. The shapefile was then converted into raster, and it could be applied to the images using EnMap 2.2.1 during the classification process.

2.4 Seagrass Meadows Mapping

The next step is image classification with the RF algorithm using shapefiles resulting from the integration of field data with Sentinel-2 imagery. This algorithm is a classification method by building a decision tree so that the results can be combined to make accurate predictions (Wicaksono et al., 2022). The decision tree divides the training sample into several parts at each node where the training data is tested so that the most useful variables can be identified (Zhang, 2015). The RF algorithm grows a "forest" of a number of trees specified by the user (n_{tree}) to produce a tree that has high variance and low bias (Breiman, 2001). The number of n_{tree} that is usually recommended is 500 (Belgiu & Drăgu, 2016). This study uses one n_{tree} scenario, namely 500 because n_{tree} has a stable value when approaching 500. n_{tree} with the best Overall Accuracy (OA) is used to continue the process on the next parameter, namely the number of features function in the form of Square Root of All Features and impurity of nodes in the form of Gini Coefficient.

The resulting Benthic Habitat Map is then tested for accuracy to determine the comparison between the image classification data and the data in the field. The analysis uses a confusion matrix that compares the data from the classification results with the model and validation samples (Lillesand et al., 2007). This analysis is calculated based on Producer's Accuracy (PA) and User's Accuracy (UA) which explain the accuracy value in each class, as well as Overall Accuracy (OA), which explains the overall accuracy. The equation is as follows.

$$Producer's\ accuracy = \frac{n_{ij}}{n_{i+j}} \times 100\% \quad (2)$$

$$User's\ accuracy = \frac{n_{ij}}{n_{i+}} \times 100\% \quad (3)$$

$$Overall\ accuracy = \frac{n_{ij}}{n} \times 100\% \quad (4)$$

Where the n_{ij} is the sample matched with the model, n_{i+j} is the total of the referenced sampel in one class, n_{i+} is the total of sample from the classification result on one class, Σn_{ij} is the total true sample from all class, and n is the total sample. The model creation produces an RF Model with .rfc format which is used to classify the five images, namely Sentinel-2 images with recording times every June-September in 2020-2024. The data are the major class classification (seagrass, macroalgae, open substrate, and coral reefs), including the area of each class. The area can be compared through tables and area graphs covering the five years of data recording. Change Detection or detection of changes in the area of seagrass meadows spatially can be done by comparing the results of the major classification of benthic habitats. The analysis was carried out on two data between adjacent years, namely 2020-2021, 2021-2022, 2022-2023, 2023-2024. Every two shapefiles of the analyzed classification results, go through the stage of merging shapefiles with the union tool so that changes in seagrass meadows can be identified. This is identified with a field calculator so that changes between classes can be identified, such as seagrass becoming Coral Reefs. The presence or absence of these changes is the basis for classifying changes in seagrass meadows into constant, decreasing, and increasing so that they can be visualized into a Seagrass Meadow Area Change Map.

2.5 Aboveground Carbon Stock (AGC) Estimation Mapping

Combination of calculations with biomass and seagrass cover data is the best way to estimate carbon stocks, but practical seagrass monitoring is recommended using cover data (percent cover) as a single data (Wahyudi et al., 2020). The formula developed by Wicaksono et al. (2021b) can be used for the classification of major benthic habitats because there is only one formula to estimate seagrass aboveground carbon stocks, not for estimation of each seagrass species. The formula is as follows.

$$AGCseagrass = 0.1028(percent\ cover) + 1.449$$

AGC calculations are carried out on ArcMap 10.8 software with a field calculator. The next step is modelling aboveground carbon stocks which can be done by regression analysis with the RF method. Regression analysis is a process in statistics so that the relationship between variables can be known (Basri, 2018). The variables used in this study are divided into independent variables in the form of image pixel values and dependent variables in the form of AGC estimation values. In this study, regression analysis with the RF method aims to map the AGC estimation of seagrass beds spatially with the formula that has been created. The input of the regression analysis with the RF method uses a test sample with a shapefile format to produce an estimation model of carbon stock above the seagrass bed surface with the .rfr format. The RF algorithm for modelling carbon stock uses the number of trees (n_{tree}) which uses one n_{tree} scenario, namely 500 because the regression results are stable approaching 500. The regression uses the number of features function in the form of Square Root of All Features and impurity of nodes in the form of Gini Coefficient.

The model obtained from the calculation and modelling of carbon stocks above the seagrass surface is then tested for accuracy so that it can be known how accurate the data produced is. The accuracy test uses three methods, namely Root Mean Square Error (RMSE), coefficient of determination (R^2), and Plot Goodness of Fit 1:1. The smaller the RMSE value indicates the increasing accuracy of the estimation results. The RMSE formula is as follows.

$$RMSE = \sqrt{\left(\left(\sum_{i=1}^{n} \frac{(x_1 - x_2)^2}{n}\right)\right)} \quad (5)$$

Where x_1 is the estimated value of modeling results, x_2 is the field result value, and n is the total sample. The 1:1 Goodness of Fit Plot is used to determine the accuracy of a model and is a tool to measure the high and low estimates of modeling from a remote sensing image (Kamal et al., 2019). This plot explains whether data is overestimated which is below the diagonal line or underestimated which is below the diagonal. In addition, the coefficient of determination *(R^2)* is a value that explains the magnitude of the relationship between variables (Arinal & Azhari, 2023). The coefficient of determination between variables will be more closely related if it approaches 100% or 1 (Syukri & Hinaya, 2019). R^2 is obtained through the regression equation graph between the modelling data and the field validation sample.

Similar to the analysis of seagrass changes, RF Model with the .rfr format is used to classify the five images, which is Sentinel-2 images with recording times of June-September 2020, 2021, 2022, 2023, and 2024 using the

EnMap Box 2.2.1 software. The data is then presented in the form of a Seagrass Carbon Stock Estimation Map for each year, illustrated in dark to light green. Dark green indicates high carbon stock, while light green indicates low carbon stock. The area can also be compared through tables and area graphs covering the five years of the recorded data. Change Detection analysis is also carried out on the spatial estimation of seagrass AGC which can be done by comparing AGC calculations. The analysis was carried out on two data between adjacent years, namely 2020-2021, 2021-2022, 2022-2023, 2023-2024. This analysis begins with the classification of changes in AGC estimates which are divided into 1) Decreased, if the AGC of the following year < AGC of the previous year, and 2) Increased, if the AGC of the following year > AGC of the previous year.

3. Results and Discussion

3.1 Seagrass Meadows Mapping

3.1.1 Accuracy Test of the Seagrass Meadows Mapping

The model produced from the creation with a model sample of 1273 points and the use of 500 trees was then tested for accuracy using a model sample of 1267 points. The results of the accuracy test can be seen in Table 1 which shows that the 190 BS Dominated, Mix Sg BS, and Sg Dominated classes have User's Accuracy and Producer's Accuracy of more than 50. Meanwhile, C Dominated, M Dominated, and Mix Sg M tend to have low accuracy. This is due to the rarity of coral reef and macroalgae objects in the study area.

Table 1. Accuracy Test Result of Benthic Habitat

Classes by the RF Classification	The						Total	UA (%)
	BS Dom	C Dom	M Dom	Mix Sg BS	Mix Sg BS	Sg Dom		
BS Dom	129	1	11	40	1	14	196	65.82
C Dom	0	1	0	0	0	0	1	100
M Dom	2	0	2	3	0	0	7	28.57
Mix Sg BS	50	5	2	257	3	140	457	56.24
Mix Sg M	0	0	0	1	0	1	2	0
Sg Dom	9	1	0	142	6	446	604	73.84
Total	190	8	15	443	10	601	1267	
PA (%)	67.89	12.50	13.33	58.01	0	74.21	OA	65.9

3.1.2 Habitat Benthic Map in the Coastal Area of Bontang City 2020-2024

As we can see from Figure 2 to Figure 6, the increase and decrease in the area of each class of benthic habitat classification results with the RF scheme shows that all classes experienced fluctuating increases and decreases from 2020 to 2024.

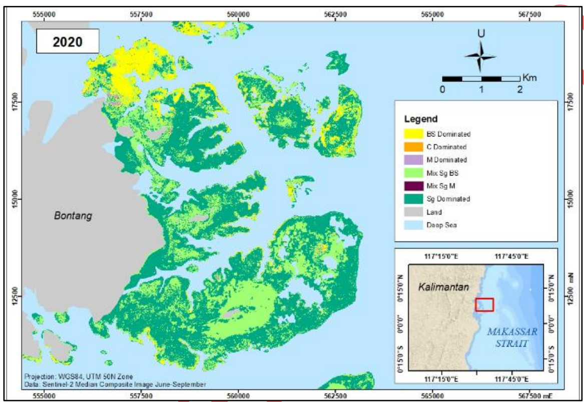

Fig 2. Benthic Habitat Map of the Coastal Area of Bontang City in 2020

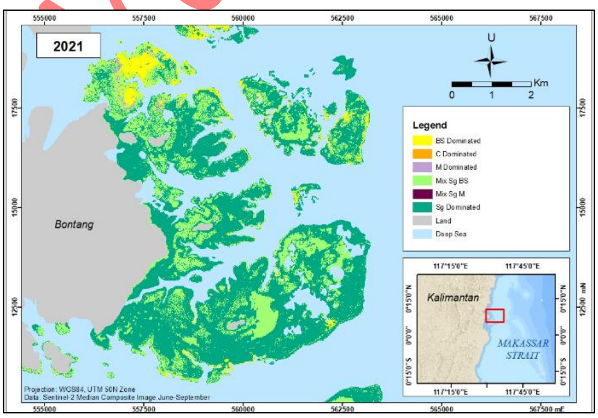

Fig 3. Benthic Habitat Map of the Coastal Area of Bontang City in 2021

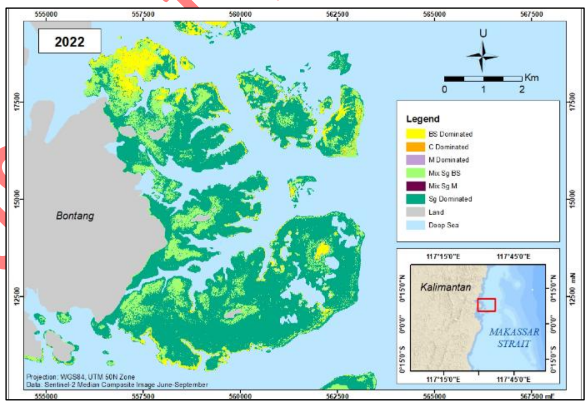

Fig 4. Benthic Habitat Map of the Coastal Area of Bontang City in 2022

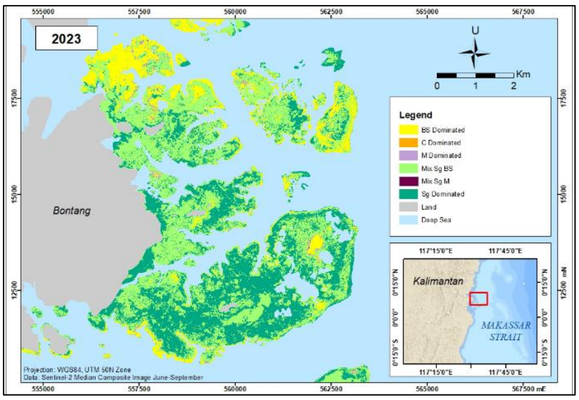

Fig 5. Benthic Habitat Map of the Coastal Area of Bontang City in 2023

The BS Dominated class experienced a decrease in 2021 with an area of 161.16 hectares then reached a peak in 2023 with an area of 437.17 hectares and decreased to 346.25 hectares in 2024. C Dominated experienced a decrease in 2021 with 2.48 hectares then increased to a peak of 15.04 hectares and decreased again in 2023 to reach 8.13 hectares in 2024. M Dominated experienced the lowest area in 2022 with an area of 3.16 hectares then reached a peak in 2023 with an area of 33.89 hectares. Mix Sg BS experienced a gradual decline until reaching its lowest area of 675.84 hectares, then increased to a peak of 1515.43 hectares and decreased again in 2024 with an area of 1079.72 hectares. Mix Sg M experienced a decline until 2022 to 1.49 hectares and increased with a peak in 2024 with an area of 5.02 hectares. Sg Dominated experienced an increase until 2022 to reach its peak at 2183.25 hectares, then decreased drastically in 2023 to 1122.51 hectares and increased again in 2024.

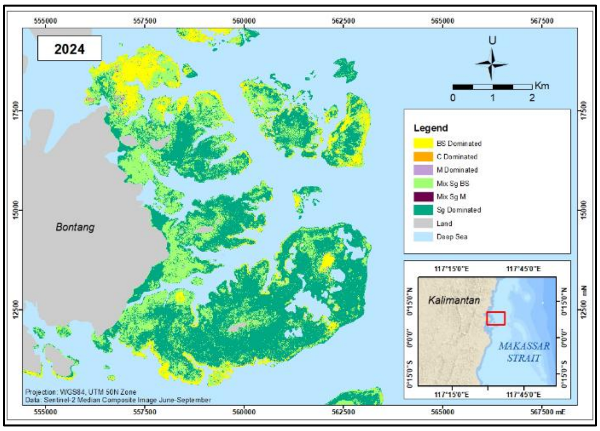

Fig 6. Benthic Habitat Map of the Coastal Area of Bontang City in 2024

3.1.3 Seagrass Meadows Distribution Map in the Coastal Area of Bontang City 2020-2024

Seagrass Distribution Map of the Coastal Area of Bontang City in 2020-2024 was made using a benthic habitat map consisting of 6 classes, namely Sg Dominated, Mix Sg BS, BS Dominated, C Dominated, M Dominated, and Mix Sg M. The six classes were then combined into Seagrass and Non-Seagrass classes. Based on Figure 7 to Figure 11, the Seagrass class consists of Sg Dominated and Mix Sg BS which have significant seagrass cover, namely more than 40%. Meanwhile, the other four classes are classified as Non- Seagrass. Based on the map of the area of seagrass beds in 2020-2024, seagrass dominates part of the coast of Bontang City. However, there is non-seagrass in the northwest of the study area. The rise and fall of seagrass experienced fluctuations starting from the rise of seagrass to reach the highest data of 2934.47 hectares in 2021, then there was a decrease to 2637.94 hectares in 2023, and increased again to 2745.94 hectares in 2024.

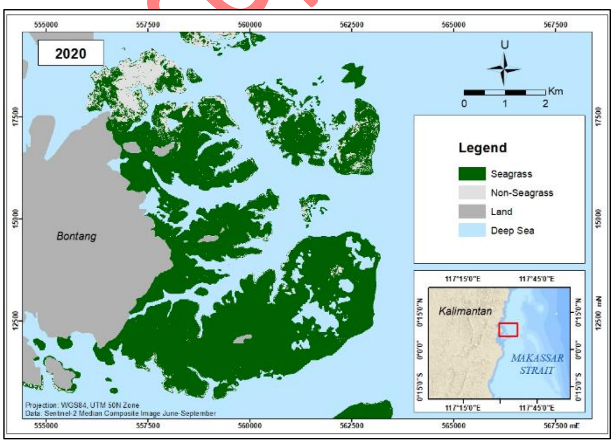

Fig 7. Seagrass Distribution Map of the Coastal Area of Bontang City in 2020

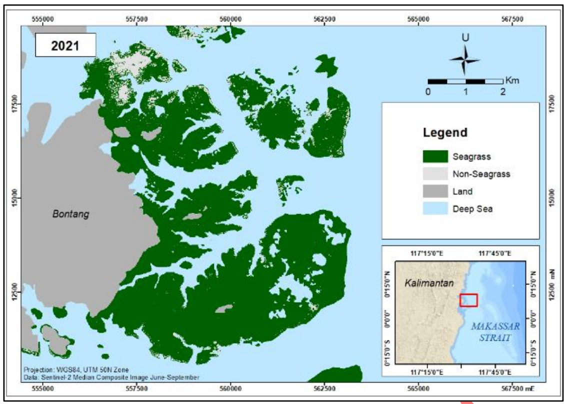

Fig 8. Seagrass Distribution Map of the Coastal Area of Bontang City in 2021

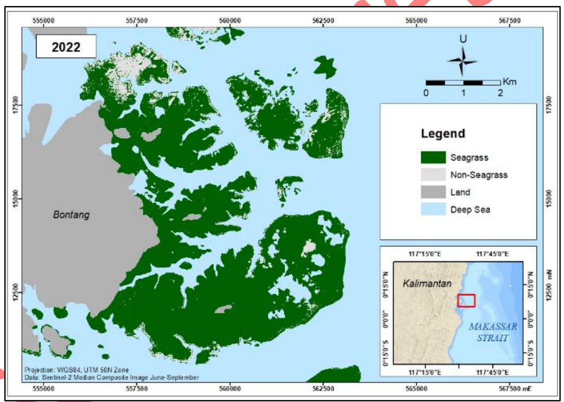

Fig 9. Seagrass Distribution Map of the Coastal Area of Bontang City in 2022

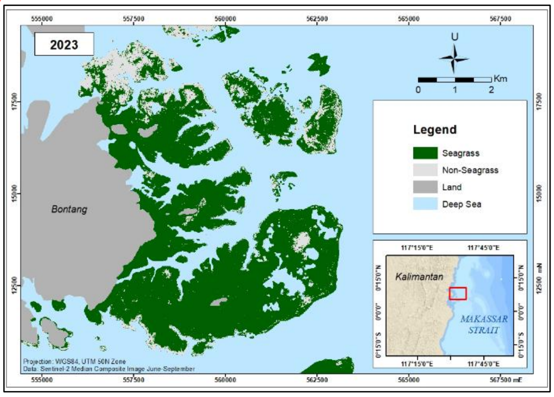

Fig 10. Seagrass Distribution Map of the Coastal Area of Bontang City in 2023

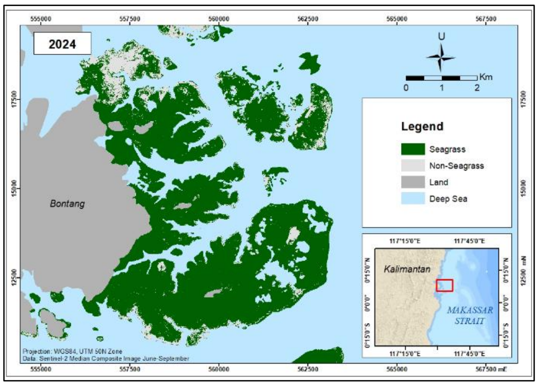

Fig 11. Seagrass Distribution Map of the Coastal Area of Bontang City in 2024

3.1.3 Seagrass Meadows Distribution Change Map in the Coastal Area of Bontang City 2020-2024

The Change of Seagrass Distribution Map of the Coastal Area of Bontang City in 2020-2024 was made by comparing two maps each consecutive year as well as maps for 2020 and 2024. The data compared were seagrass and non - seagrass, so the changes between classes could be identified. Changes from non-seagrass to seagrass became a class that explained the increase in seagrass area or referred to as the Increased class. Changes from non-seagrass to seagrass became a class that explained the reduction in seagrass area or referred to as the Decreased class. Seagrass that remains seagrass is referred to as the Same class. Meanwhile, non-seagrass that remains non-seagrass is referred to as the Non-Seagrass class.

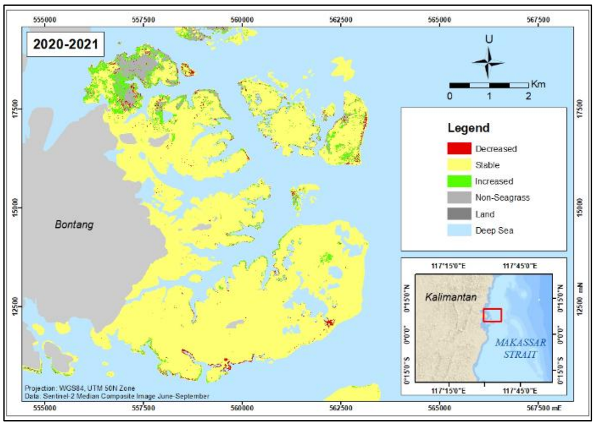

Fig 12. Change of Seagrass Distribution Map of the Coastal Area of Bontang City from 2020 to 2021

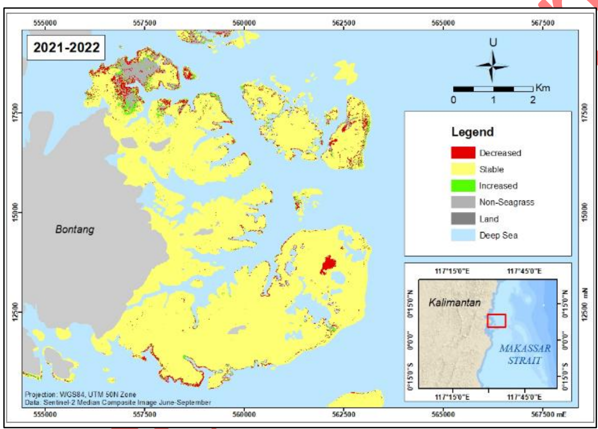

Fig 13. Change of Seagrass Distribution Map of the Coastal Area of Bontang City from 2021 to 2022

The Change of Seagrass Distribution Map of the Coastal Area of Bontang City in 2020-2024 from Figure 12 to Figure 16 shows that the seagrass is dominated by the stable seagrass of 2643.92 hectares (84.78%). The decreased seagrass on the map looks quite significant with an area of 164.21 hectares (5.27%). The decreasing seagrass area in the comparison of 2020 and 2024 data is seen to dominate the northeastern part of the study area which occurred in 2022-2023. There is also a reduction in seagrass distribution in the southern part of the study area which occurred in 2021-2022 and 2022-2023. The decreasing seagrass area is not much different from the non-seagrass area of 208.47 hectares (6.68%). Meanwhile, the increasing seagrass has a small area of 102.02 hectares (3.27%). The increasing seagrass dominates the northern part of the study area which increased in 2020 -2021 and 2023-2024. The class with increasing seagrass area shows that there is a decrease in seagrass until 2022-2023 to 43.77 hectares, then increases again to 203.52 in 2023-2024. The class with decreasing seagrass area shows an increase to 264.93 hectares in 2022-2023, then decreases to 95.52 in 2023-2024. The class with a constant seagrass area shows a slight increase to 2800.57 hectares in 2021-2022, then decreases to 2542.42 hectares in 2023-2024. Meanwhile, the non-seagrass class tends to increase to 277.15 hectares in 2023-2024 although it has decreased to its lowest point at 125.61 hectares in 2021 -2022.

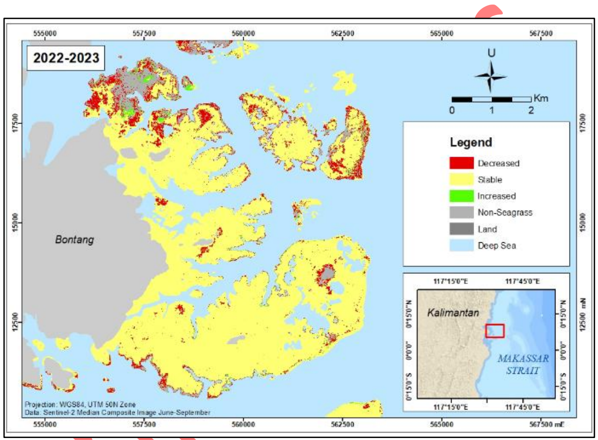

Fig 14. Change of Seagrass Distribution Map of the Coastal Area of Bontang City from 2022 to 2023

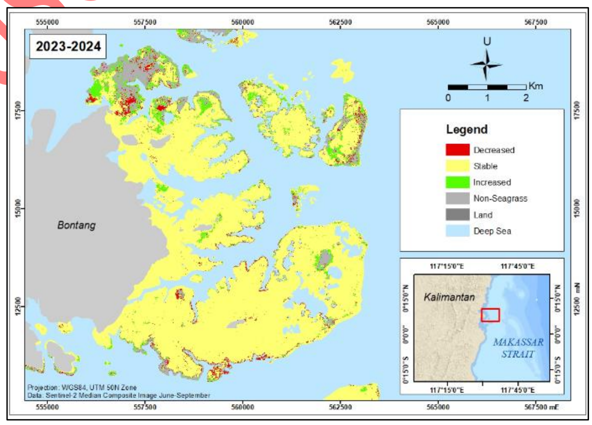

Fig 15. Change of Seagrass Distribution Map of the Coastal Area of Bontang City from 2023 to 2024

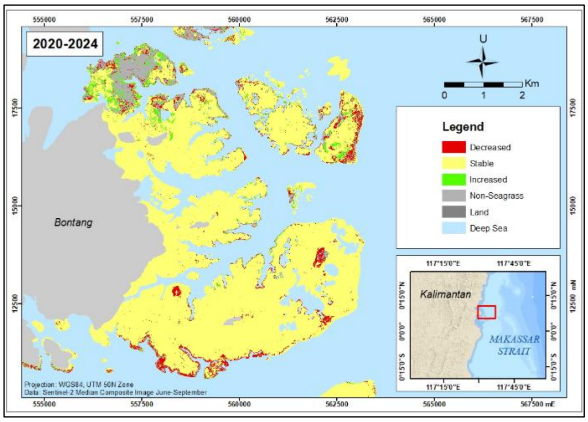

Fig 16. Change of Seagrass Distribution Map of the Coastal Area of Bontang City from 2020 to 2024

3.2 Aboveground Carbon Stock (AGC) Estimation Mapping

3.2.1 Accuracy Test of AGC Estimation Mapping

The results of the seagrass AGC modeling in this study were tested for accuracy to determine the accuracy of the model produced to estimate and map seagrass AGC in part of the coast of Bontang City (Table 2). The accuracy test was carried out with Plot 240 Goodness of Fit 1: 1, RMSE, and R^2 using a validation sample of 1267 points.

Table 2. RF Accuracy Test Result

RF Accuracy Test		
Sample	N	1267
Root Mean Squared Error	RMSE	2.09 gC/m^2
Squared pearson correlation	R^2	0.65

Accuracy testing with RMSE is carried out to determine the error in the data. The smaller the RMSE, the more accurate the data. The AGC model that has been created has an RMSE of 2.09 gC/m^2 which explains that there is an error of 2.09 gC in every square meter. Meanwhile, determination (R2) explains the magnitude of the relationship between variables 245 (Arinal & Azhari, 2023). The coefficient of determination between variables will be more closely related if it approaches 100% or 1 (Syukri & Hinaya, 2019). The R2 resulting from the AGC model accuracy is 0.65, which means that the AGC estimation model can explain 65% of the total variation in AGC data.

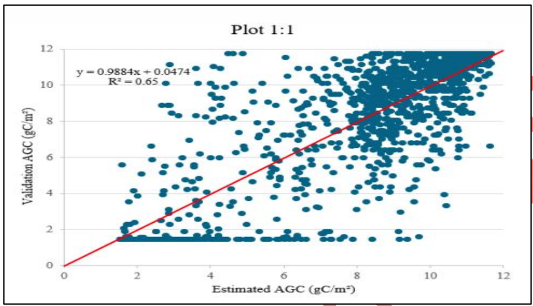

Fig 17. Change of Seagrass Distribution Map of the Coastal Area of Bontang City from 2020 to 2024

Figure 17 explains the relationship between the estimated carbon stock above the seagrass meadow resulting from modelling on the x-axis with the carbon stock above the seagrass meadow obtained from field activities on the y-axis. The graph explains that the results of the estimated carbon stock have good accuracy because the points produced tend to follow the red line because the relationship between the estimated AGC and the field AGC is stronger the closer it is to the red line. The R2 produced in making this plot also has the same value as the R2 made in the RFR accuracy test, which is 0.65. Although it tends to have good accuracy, the 1:1 Goodness of Fit plot explains that there are many points that are overestimated and underestimated. Overestimated is a condition when the estimated results exceed the results obtained in the field. Based on the graph, the data that is overestimated is the field AGC data which has a value of 1.449 gC/m^2. The data is estimated to be with various estimates, even up to around 8 gC/m^2. Meanwhile, underestimated is a condition when the estimated results are less than the results obtained in the field. The 1:1 Goodness of Fit plot explains that the underestimated field AGC data is around 10 to 12 gC/m^2 which is estimated to be 8 to 10 gC/m^2.

3.2.2 AGC Estimation Map in the Coastal Area of Bontang City 2020-2024

The AGC Estimation Map of the Coastal Area of Bontang City in 2020-2024 was created using classes from the benthic habitat map consisting of Sg Dominated, Mix Sg BS, and BS Dominated. Unlike the Seagrass Distribution Map, BS Dominated is used to estimate AGC with low seagrass percent cover. Based on the AGC Estimation Map of the Coastal Area of Bontang City in 2020-2024 from Figure 18 to Figure 22, seagrass with high AGC dominates the coast of Bontang City. However, there is seagrass with low AGC estimates in the northern part of the study area. Seagrass AGC experienced fluctuations starting from an increase in seagrass to reach the highest data of 300.26 tons in 2021, then there was a decrease to reach 247.58 tons in 2023 and increased to 265.6 tons in 2024.

AGC Estimation Map of the Coastal Area of Bontang City in 2020-2024 is divided into four classes based on the amount of AGC in each square meter, namely <3 gC/m^2, 3-6 gC/m^2, 6-9 gC/m^2, and >9 gC/m^2. The study area is dominated by seagrass with AGC >9 gC/m^2 which experienced an increase in area to 2383.38 hectares in 2021, then decreased to reach its lowest point of 1270.97 hectares in 2023 and increased again to 1685.32 in 2024. The next data is AGC with a range of 6-9 gC/m^2 which has the opposite fluctuation to the class >9 gC/m^2, namely decreasing slightly to 414.35 hectares in 2021, increasing to a peak of 1154.57 hectares in 2023, then decreasing to 902.3 6 hectares in 2024. Meanwhile, the class with AGC <3 gC/m^2 and 3-6 gC/m^2 experienced quite similar fluctuations, namely decreasing slightly in 2021 (105.79 hectares and 192.11 hectares), increasing to a peak in 2023 (291,30 hectares and 358,14 hectares), then slightly down in 2024 (188,79 hectares and 315,71 hectares).

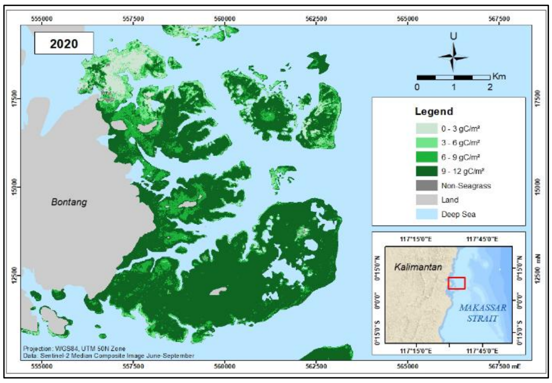

Fig 18. AGC Estimation Map of the Coastal Area of Bontang City in 2020

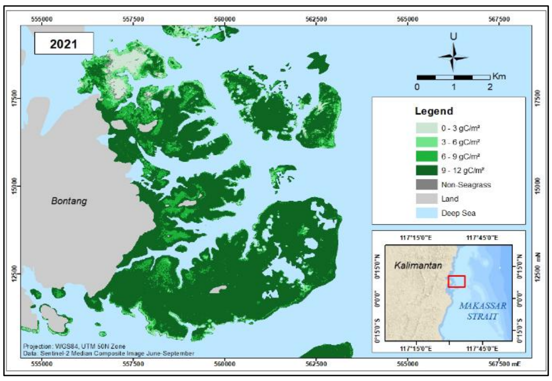

Fig 19. AGC Estimation Map of the Coastal Area of Bontang City in 2021

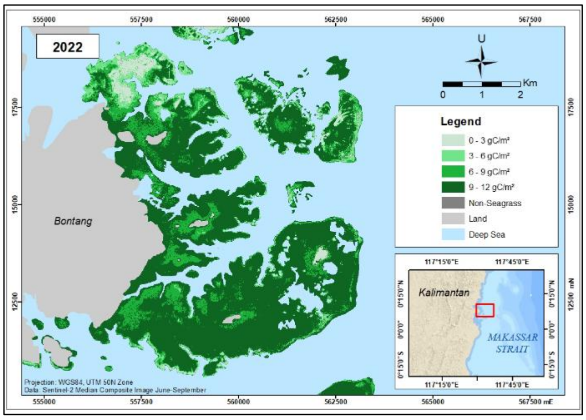

Fig 20. AGC Estimation Map of the Coastal Area of Bontang City in 2022

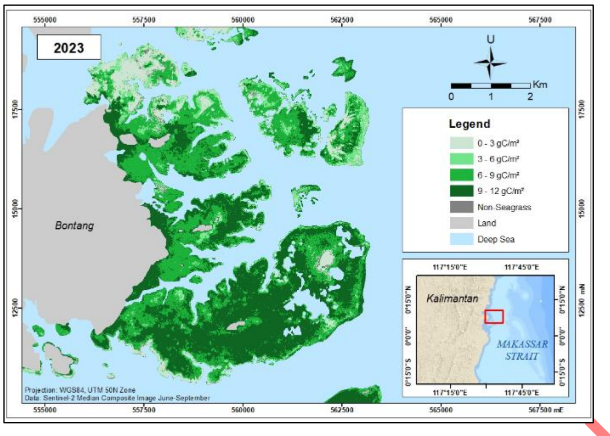

Fig 21. AGC Estimation Map of the Coastal Area of Bontang City in 2023

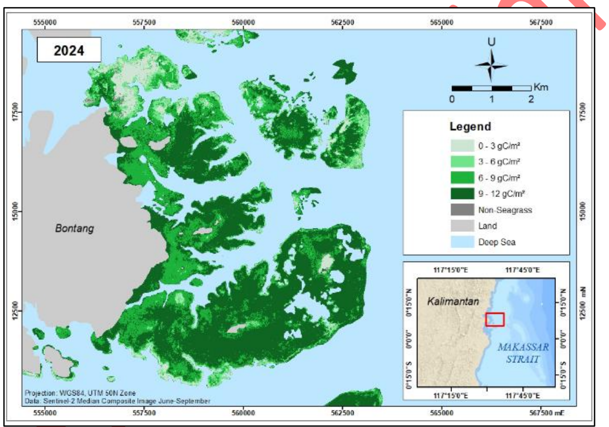

Fig 22. AGC Estimation Map of the Coastal Area of Bontang City in 2024

3.2.3 AGC Estimation Change Map in the Coastal Area of Bontang City 2020-2024

The year-to-year chronological breakdown shows that the proportion of increasing and decreasing seagrass Above-Ground Biomass Carbon (AGC) varies significantly over time. According to Figure 23, the decreasing seagrass AGC is 1,303.95 hectares (42.45%) in 2020–2021, which increases to 1,566.54 hectares (50.92%) in 2021–2022 based on Figure 24. It then increases significantly to 2,548.29 hectares (83.39%) in 2022–2023 based on Figure 25, before dropping drastically to 1,155.01 hectares (37.87%) in 2023–2024 based on Figure 26. Meanwhile, the increasing seagrass AGC moves in inverse proportion to the decreasing trends. The increased AGC of seagrass covers an area of 1,767.72 hectares (57.55%) in 2020–2021 (Figure 23), decreases slightly to 1,509.75 hectares (49.08%) in 2021–2022 (Figure 24), decreases drastically to 507.46 hectares (16.61%) in 2022–2023 (Figure 25), and finally increases significantly to 1,894.70 hectares (62.13%) in 2023–2024 (Figure 26). Finally, the overall AGC Change Map of the Coastal Area of Bontang City 2020–2024 in Figure 27 reveals that the net change across the entire period is heavily dominated by a loss in seagrass, with a total decreasing area of 2,133.2 hectares (69.53%) compared to an increasing area of 934.94 hectares (30.47%)..

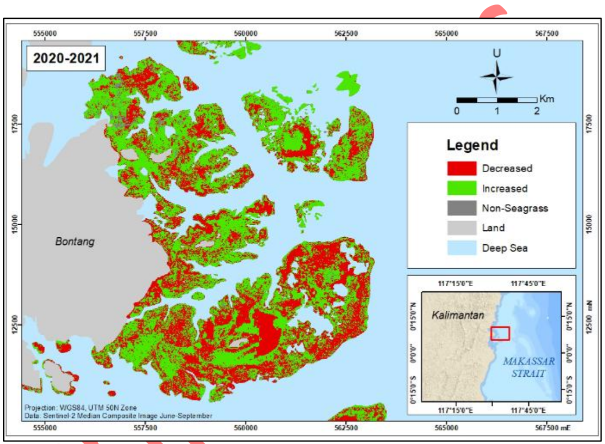

Fig 23. AGC Change Map of the Coastal Area of Bontang City from 2020 to 2021

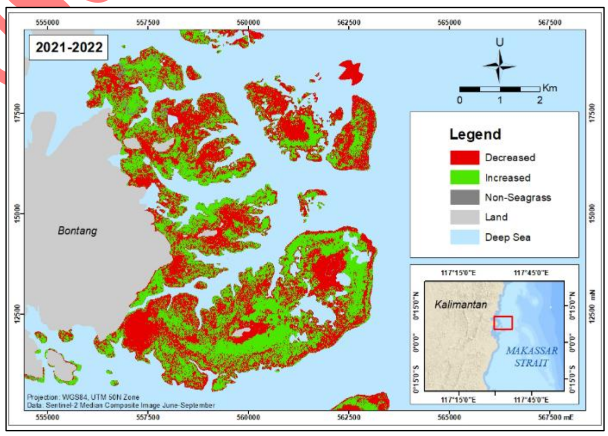

Fig 24. AGC Change Map of the Coastal Area of Bontang City from 2021 to 2022

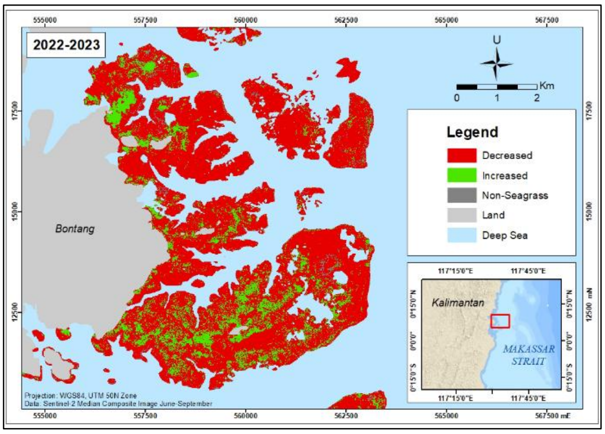

Fig 25. AGC Change Map of the Coastal Area of Bontang City from 2022 to 2023

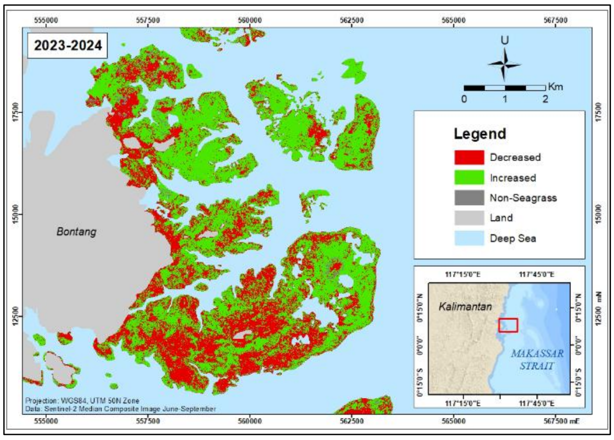

Fig 26. AGC Change Map of the Coastal Area of Bontang City from 2023 to 2024

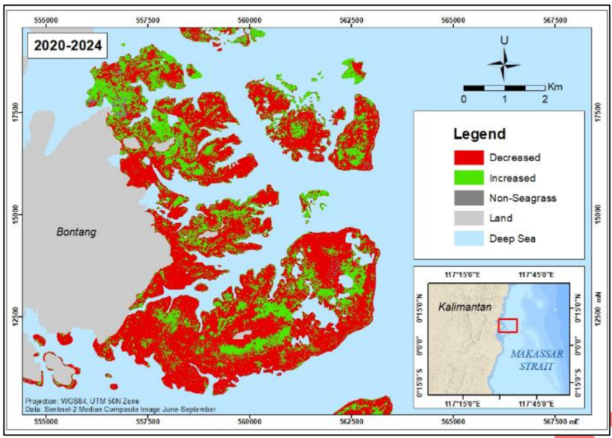

Fig 27. AGC Change Map of the Coastal Area of Bontang City from 2020 to 2024

3.2.4 Mean and Coefficient Variation of the AGC Map in the Coastal Area of Bontang City 2020- 2024

Figure 28 is a map that presents data in the form of the average AGC of seagrass beds spatially. This average is obtained from AGC processing data for each year. Similar to the AGC map that presents data for each year, this map is divided into four classes based on the grams of carbon produced by seagrass beds, namely less than 3, 3-6, 6-9, and more than 9. Based on the map, seagrass beds with an AGC of more than 9 gC/m^2 dominate the study area, especially in the southern and central parts with an area of 2016.48 hectares (64.66%) and a total AGC of 209.53 tons. This class is then followed by seagrass with 6-9 gC/m^2 which has an area of 617.26 hectares (19.79%) and a total AGC of 49.53 tons. Meanwhile, the class with an average AGC of 3-6 gC/m^2 of seagrass beds is 258.14 hectares (8.28%) with a total AGC of 11.62 tons and the class 0-3 gC/m^2 is 98.32 hectares (3.15%) with a total AGC of 2.35 tons. There is also a non-seagrass class in the study area of 128.4 hectares (4.11%). The average of the total AGC is also measured by Sentinel-2 image processing in the range of June-September 2020-2024 each year is 273.02 tons.

The measurement of the coefficient of variation (CV) was also carried out to determine the consistency of pixels in multitemporal images, which explains that the large CV value will drive high pixel variation (Salsabila, 2024). Figure 29 shows the CV in the AGC estimation of seagrass beds in part of the coast of Bontang City with numbers from 0 to 109.43. Visually, most of the study areas classified as seagrass beds have a CV with a range of 0-27.36, which explains that seagrass has a consistent AGC compared to other classes. Based on area measurements using the Calculate Geometry tool in ArcMap 10.8, the area of the study area that has a CV with a range of 0-10 gC/m^2 is 1497,96 hectares (48.03%). As much as 1451,95 hectares of the study area (48,03%) has a CV between 10-50 gC/m^2 which is located in the northern part of the study area. Only 40.72 hectares of the study area (1.29%) have a more than 50 gC/m2 CV.

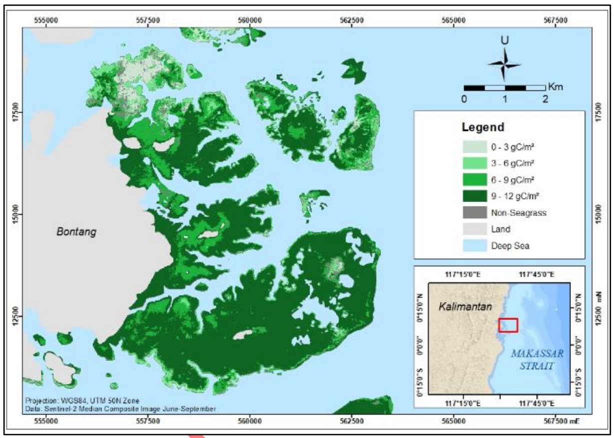

Fig 28. Mean of AGC Map of the Coastal Area of Bontang City

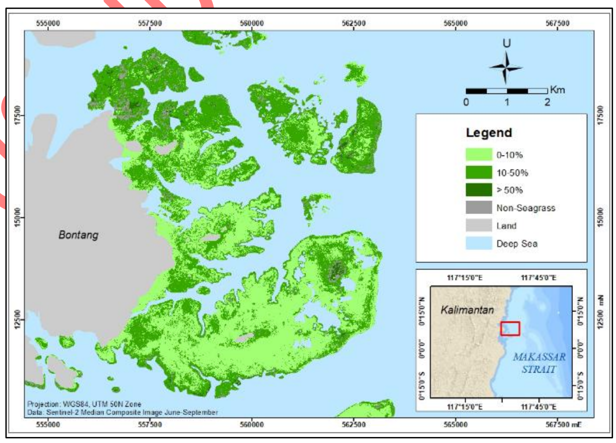

Fig 29. Coefficient Variation of AGC Map of the Coastal Area of Bontang City

4. Conclusion

This study comprehensively evaluates the changes in seagrass meadow distribution and its associated AGC dynamics within the coastal area of Bontang City from 2020 to 2024. To establish the reliability of these findings, the benthic habitat mapping achieved an Overall Accuracy of 65.9%. In terms of spatial distribution, the benthic habitat is consistently dominated by the "Sg Dominated" and "Mix Sg BS" classes across the optically shallow waters. Over the four-year period, the total seagrass extent exhibited a net decline from 2,808.88 hectares in 2020 to 2,745.94 hectares in 2024, despite a temporary peak of 2,934.48 hectares in 2021. Overall, the coastal area is characterized by high stability, with 2,643.92 hectares (84.78%) remaining unchanged. However, losing trends outpaced gains, as the degraded seagrass area spanned 164.21 hectares (5.27%) compared to just 102.02 hectares (3.27%) of newly colonized seagrass. Parallel to the spatial decline, the total estimated seagrass AGC stock across the 3,118.6-hectare study area generally decreased from 287.12 tons of carbon in 2020 to 265.6 tons of carbon in 2024. A direct image comparison between 2020 and 2024 reveals that the study area was heavily dominated by net carbon loss, with 2,133.20 hectares (69.53%) experiencing a decrease in AGC, while only 934.94 hectares (30.47%) showed an increase. Despite this decline, high-density carbon zones persisted, with annual and average data showing that the study area remains dominated by seagrass with an AGC density exceeding 9 gC/m^2 The AGC estimation model demonstrated strong reliability, yielding a RMSE of 2.09 gC/m^2, an R^2 of 0.65 and a 1:1 Plot Goodness of Fit, confirming a robust positive correlation between the estimated and field-measured AGC samples.

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