Remote Sensing-Based Assessment of How Much Tropical Wetland Fires Contribute to Carbon Emissions and How Fast the Carbon Recovering Is

by Abdi Fithria

Remote Sensing-Based Assessment of How Much Tropical Wetland Fires Contribute to Carbon Emissions and How Fast the Carbon Recovering Is

ABDI FITHRIA[1,2,*], SYAMANI D. ALI[1,2], AND ARFA A. REZEKIAH[1]

[1]Faculty of Forestry, Lambung Mangkurat University, Banjarbaru, Indonesia
[2]Center for Geospatial Information Infrastructure Development, Lambung Mangkurat University, Banjarbaru, Indonesia

ABSTRACT

This research had two objectives. The first objective was to quantity the carbon emissions from fires of various types of tropical wetland vegetation using Sentinel-2 imagery. The second objective was to measure how long the carbon stock will recover using Sentinel-2 imagery. Burned areas were extracted automatically using the Relativized Burn Ratio (RBR). Calculation of carbon emissions and carbon sequestrations were carried out by measuring the differences in Above Ground Biomass (AGB) before the fires, right after the fires, and a few months after the vegetation re-grows after the fires. Therefore, multitemporal Sentinel-2 MSI imageries from three different times are required. All imageries processing was carried out using the ESA SNAP software. The results showed that tropical wetland fires emitted an average of 121.61 Mg C/ha, or equivalent to 445.9 Mg CO_2/ha. Furthermore, tropical wetlands had an average rate of about 9.27 months to restore their carbon stocks to their pre-burnt state. Peatland forests took the longest time to recover to its original carbon stock state after burning, which was almost 22 years to recover.

Keywords: Tropical wetlands, fires, biomass, carbon emissions, remote sensing

INTRODUCTION

According to the Global Lakes and Wetlands Database Level 3 (GLWD Level 3), the total area of South Kalimantan's wetlands is 8,877.56 square kilometers (Lehner and Doell, 2004). If the total land area of South Kalimantan Province is 38,744.23 square kilometers (BPS-Statistics of Kalimantan Selatan Province, 2021), it means that the wetlands area of South Kalimantan is about 23% of the total land area. Although the GLWD Level 3 wetlands data is actually geospatial data that has a coarse spatial resolution of 30 arc-seconds, or about 1 kilometer (Lehner and Doell, 2004).

Correspondence Author: Abdi Fithria, Faculty of Forestry, Lambung Mangkurat University, Jl. Ahmad Yani, km.35, Banjarbaru, email: mksfabdi@ulm.ac.id

Therefore, it is possible that the actual wetlands in the field are wider than those mapped by GLWD Level 3. Of course, as an area around the equator, the wetlands in South Kalimantan are tropical wetlands, which is dominated by green vegetation such as swamp forest, peatland forest, swamp shrubs and bushes, mangroves, agricultural crops, and so on.

The main environmental problems faced by the province of South Kalimantan and all provinces on the island of Kalimantan are the forest and land fires that hit some areas during the dry season. Aside from humans, the main causes of fires are dry weather conditions caused by decreased rainfall (Imanudin et al., 2018). Based on the results of Syam'ani (2020), most of the forest and land fires in South Kalimantan occur in wetland areas. This is, of course, a major blow to the vegetation biomass or carbon stocks stored in the wetlands of South Kalimantan. Forest and land fires will burn carbon stocks contained in vegetation biomass and will release these carbon stocks in the form of carbon emissions into the earth's

48

atmosphere. The impact of too much carbon dioxide in the atmosphere is global warming and global climate change.

One of the specific challenges related to carbon emissions from wetland fires is how to measure or quantify the carbon emissions resulting from the fires. This includes how to measure the rate of recovery of carbon stocks or wetland vegetation biomass after experiencing fires. This is certainly useful for determining protection or conservation actions, including environmental restoration efforts in the future. Some types of wetland vegetation will recover on their own in a short time after experiencing fires, and some wetland vegetation may take a relatively long time to recover after fires. For wetland vegetation that takes a long time to recover after fires, or even has the potential to not recover naturally, of course it requires the role or actions of humans to help it recover to its original state. Certain wetland vegetation, such as agricultural crops, will actually be restored by humans through planting activities.

Various methods can be implemented to quantify carbon emissions from wetland fires, including measuring the rate of recovery of carbon stocks. The most accurate method is, of course, field measurements. Namely by measuring the biomass of wetland vegetation before the fire incident, right after the fire incident, and some time when the vegetation began to recover after the fire. Of course, field measurement is not an efficient process, because it will be very time-consuming, labor-intensive, and costly. In addition, the measurement coverage area will be very limited and sometimes we have to use destructive sampling. Another method that is considered quite efficient in the quantification of biomass or vegetation carbon stock is the use of remote sensing technology.

Several remote sensing satellite imageries are available free of charge from the providers on the internet. Among them are Landsat series, ASTER, Sentinel-2, and Sentinel-3. Sentinel-2 Multispectral Instrument (MSI) are satellites owned by the European Space Agency (ESA). Sentinel-2 is a twin satellite, namely Sentinel-2A and Sentinel-2B, which is capable of acquiring the same location on the earth's surface every five days. The ability of Sentinel-2 MSI imagery to extract vegetation biomass information is unquestionable. Various research results have proven this.

Askar et al. (2018) estimated Above Ground Biomass (AGB) on private forest using Sentinel-2 imagery, and they found a significant correlation coefficient (R2) of 0.81. Torabzadeh et al. (2019) estimates AGB of vegetation in Zagros Forest, Iran, using Sentinel-2. They found R2 of 0.87 and Root Mean Square Error (RMSE) of 10.75 ton/ha. Imran et al. (2020) used narrow band based and broadband derived vegetation indices extracted from Sentinel-2 to estimate vegetation biomass in Pakistan. They found a correlation coefficient (R2) of up to 0.64. Kumar et al. (2021) estimated forest AGB using Sentinel-2 in Jharkhand state, India. They found an accuracy of up to 90%. Li et al. (2021) estimated AGB for Grassland in the Shengjin Lake Wetland, China using Sentinel-2. They found the correlation coefficient (R2) above 0.8.

Chen et al. (2020) used a combination of Landsat and Sentinel-2 to estimate the biomass of rubber plantations on Hainan Island, China, they used Random Forest (RF). The accuracy of the estimated biomass resulting from this research (R2) of 0.79 and Root Mean Square Error (RMSE) of 14 Mg/ha. Pang et al. (2020) estimated grassland AGB on the Inner Mongolia Plateau using the simulated spectra of Sentinel-2. Their research resulted in an accuracy (R2) of 0.95. Chen et al. (2021) estimated pasture biomass using Sentinel-2 imagery and machine learning in Tasmania, Australia. Their research yielded an R2 of 0.6.

48

Vuorinne et al. (2021) measured leaf biomass of Agave sisalana using Sentinel-2 vegetation indices. They yielded 76% accuracy and RMSE 5.15 Mg/ha.

Fang et al. (2021) mapped biomass crops in Hebei Province, China, using Sentinel-2 and Improved CASA Model. Their research results showed an accuracy of 0.7 and 0.73. He et al. (2021) mapped crop biomass using Sentinel-2 in Manitoba, western Canada. They confirmed that the average accuracy value above 80%. Naik et al. (2021) used Sentinel-2, RapidEye, and Dove satellites to predict forest AGB in the Province of Trento, Italy. They showed that for Sentinel-2 it had an R2 of 0.53. Kumar et al. (2021) conducted a rapid evaluation and validation method of forest AGB assessment using Sentinel-2. Their research results inform that the Modified Soil Adjusted Vegetation Index (MSAVI) (Qi et al., 1994) transformation method implemented on Sentinel-2 imagery is able to provide the most accurate AGB calculation results.

Based on the fact that remote sensing technology, such as Sentinel-2 imagery is adequate in extracting vegetation biomass information from space. Therefore, we will be able to calculate the loss of vegetation carbon stock, or in other words is the carbon emission, in the event of fires. Because carbon stocks have a direct correlation with vegetation biomass. This research has two objectives. First, to assess the quantity of carbon emissions into the earth's atmosphere from fires of various types of tropical wetland vegetation using Sentinel-2 MSI imagery. Second, to assess how fast or how long the carbon stock will recover using Sentinel-2 MSI imagery.

MATERIAL AND METHODS

This research was conducted in entire of South Kalimantan Province and parts of Central Kalimantan Province, as shown in Figure 1. The total research area is more than 3,000,000 hectares. The main reason for choosing this research location is that most of the fires in South Kalimantan and Central Kalimantan occur in this area, and almost the entire area are wetlands. This research takes cases of fire disasters that occurred in South Kalimantan and central Kalimantan during the dry season in 2019. Most of the forest and land fires that occurred in 2019 in South Kalimantan and Central Kalimantan took place in wetlands. It should be emphasized here, that we will not calculate the total carbon emissions due to fires in an area. What we will calculate in this research is how much carbon emissions will be contributed by each type of wetland cover vegetation. Including how quickly each of these vegetation will restore its biomass or carbon stock.

Figure 1. Research location

Because this research aims to measure carbon emissions resulting from the fires, as well as to measure the recovery of carbon stocks after experiencing fires, multitemporal imageries from three different times are needed. That is before the fires (referred as prefires hereafter), after the fires (referred as postfires hereafter), and several months after the vegetation starts to grow back after the fires (referred as regrowth hereafter). For the prefires time, taken from the time of the acquisition of Sentinel-2 imagery on June 30, 2019, because June is usually the

end point of the rainy season at the research location. For postfires time, taken from the acquisition of Sentinel-2 imagery on September 13, 2019, at this time some research areas had experienced fires. For regrowth time, taken from the time of the acquisition of Sentinel-2 imagery on May 5, 2020, where at this time, most of the vegetation has grown back.

Sentinel-2 MSI imageries used were Sentinel-2 MSI level 2A, which means atmospheric correction has been made. Of the three image acquisition times used, each acquisition time required three Sentinel-2 imageries tiles. Therefore, there were total of nine Sentinel-2 imageries required, with total imageries capacity of more than nine Gigabytes. These imageries processing requires sufficient computer resources. Sentinel-2 MSI imagery has 13 spectral bands, with variations in spatial resolution of 10 meters, 20 meters, and 60 meters (European Space Agency, 2012). For analysis purposes, the spatial resolution of all bands was resampled to 10 meters. The entire process of processing Sentinel-2 imageries in this research was carried out using the European Space Agency Sentinel Application Platform (ESA SNAP) software. The opensource ESA SNAP software is provided by the European Space Agency (ESA) at free of charge. This software is written using the Java Programming Language. Sentinel-2 imageries that had been resampled were then mosaiced and stacked, so that all imageries from the three acquisition times were combined into one file. This is necessary for mapping burned areas and analyzing changes in biomass or carbon stocks.

After the preprocessing of Sentinel-2 imageries is complete, the next step was mapping the burned areas. In mapping burnt areas, the method used was the Relativized Burn Ratio (RBR), which is formulated as follows (Parks et. al., 2014):

$$RBR = \frac{NBR_{prefire} - NBR_{postfire}}{NBR_{prefire} + 1.001}$$

The Normalized Burn Ratio (NBR) was calculated as follows (Lopez, 1991; Key and Benson, 1995; and Koutsias and Karteris, 2000):

$$NBR = \frac{NIR - SWIR2}{NIR + SWIR2}$$

Where:
NIR = Near Infrared band of Sentinel-2 (band 8)
SWIR2 =Shortwave Infrared band of Sentinel-2 (band 12)

The RBR resulted a single image with pixel values in the range of -0.5 to 1.3. Since Syam'ani (2020), used the Otsu thresholding method (Otsu, 1979) to separate the burned area and unburned area on the Sentinel-2 RBR in the same location, obtained a threshold value of 0.15, we then used a threshold value of 0.15 in present research. In the burned areas, purposive sampling will then be assigned to each type of wetland vegetation. Which includes swamp shrub and bushes, swamp grass, swamp forests, peat swamps, peatland shrub and bushes, peatland forests, rice fields, wetland plantations, and other wetland agricultural plants.

Assuming that the fire event only burned parts of the above ground vegetation, then vegetation Above Ground Biomass (AGB) was extracted from the three acquisition times of Sentinel-2 imageries using the following formula (Askar et. al., 2018):

$$AGB = 537NDI45 + 158.42EVI - 353.66$$

The Normalized Difference Index 45 (NDI45) was calculated as follows (Delegido et. al., 2011):
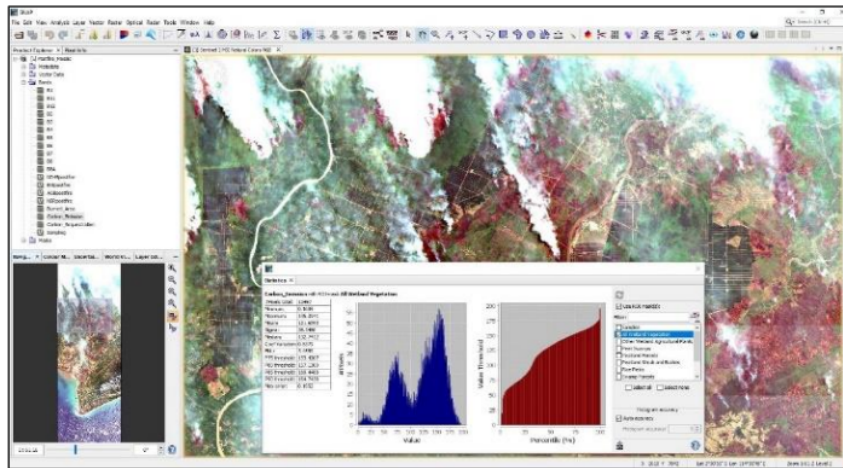
51

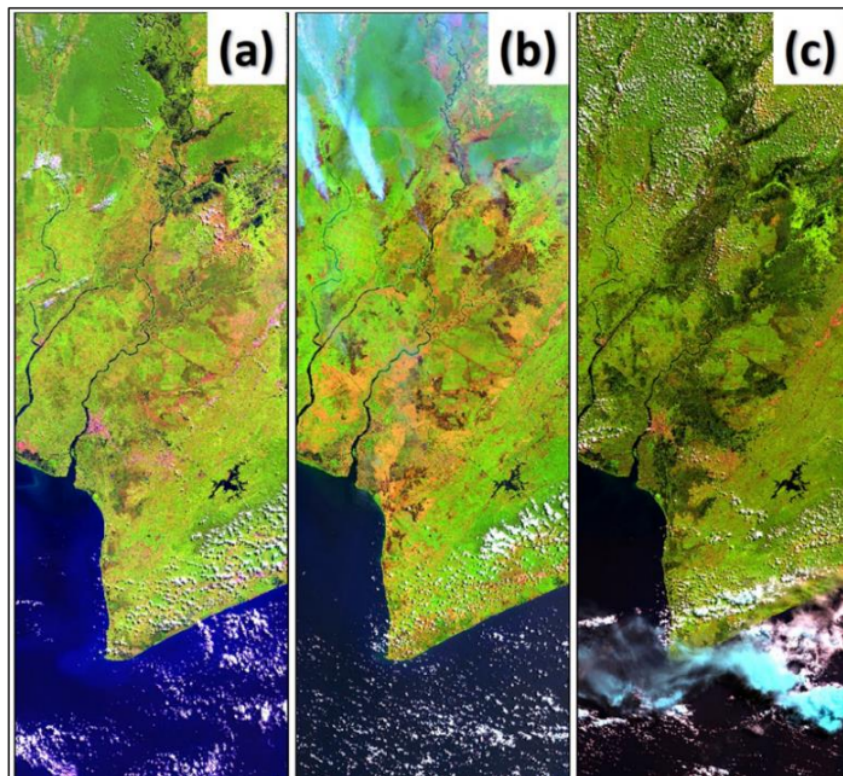Figure 2. Carbon emissions calculation in ESA SNAP software

Figure 3. (a) Prefires imagery, (b) Postfires imagery, and (c) Regrowth imagery.

52

$$NDI45 = \frac{RE1 - Red}{RE1 + Red}$$

And the Enhanced Vegetation Index (EVI) was calculated as follows (Huete et. al., 2002):

$$EVI = 2.5 \left(\frac{NIR - Red}{NIR + 6Red - 7.5Blue + 1} \right)$$

Where:
RE1 = Red Edge 1 band of Sentinel-2 (band 5)
Red = Red band of Sentinel-2 (band 4)
Blue = Blue band of Sentinel-2 (band 2)

The AGB formula used in this research will produce vegetation biomass in Mg/ha units. According to Ma et al. (2018), the percentage of organic carbon stored in vegetation biomass ranges from 45% in reproductive organs to 47.9% in stems. For simplicity, we took the average value, that was 46.45%. To calculate carbon emissions resulting from fires, the method was by substracting postfires AGB from prefires AGB in burned areas. Meanwhile, to calculate the rate of carbon stock recovery, the method was by subtracting the AGB regrowth from AGB postfires in burned areas, then dividing by the time interval from postfires to regrowth. Figure 2 shows an overview of how the process of calculating carbon emissions using the ESA SNAP software.

The carbon emissions was converted into carbon dioxide (CO_2) equivalent by multiplying the results of the calculation of carbon emissions by a constant value of 3.67.

RESULTS

Figure 3. shows how atmospheric disturbance in the prefires, postfires, and regrowth imageries were. The prefires imagery was not the last imagery to be acquired at the end of the rainy season—in terms of mapping fires and estimating carbon emissions from fires as ideal. This indicated that after acquisition of the prefires imagery, there was rains until the end of the dry season.

Table 1 shows the estimated results of carbon emissions from wetland fires in Mg/ha, as well as the rate of recovery of carbon stocks in Mg/ha/month. Because the postfires imagery was acquired on September 13, 2019, while the regrowth imagery was acquired on May 5, 2020, then there will be an interval of 235 days or about 7.8 months from postfires to regrowth. To calculate the rate of recovery of carbon stocks, the result of subtraction between regrowth above ground carbon and postfire above ground carbon must be divided by 235 days, then multiplied by 30 days (assuming the number of days in a month).

For each type of wetland vegetation, such as peatland forests, it is certain that there will be variations in biomass. Including when fires occur in the peatland forests, it is certain that the severity of the fires will not be the same throughout the peatland forest area. Therefore, Table 1 provides information on the range of carbon emissions from minimum to maximum, and average carbon emissions for each type of wetland vegetation. Likewise, information on the rate of carbon recoveries, which are also presented in the form of a range from minimum to maximum and the average value.

Table 2 is a conversion from Table 1, where carbon emissions are converted to CO_2 equivalent emissions in Mg/ha units. Meanwhile, the rate of carbon recovery was converted into CO_2 sequestration in units of Mg/ha/month. From Table 2 and Figure 5 it can be seen that the sequences of CO_2 emissions per hectare were other wetland agricultural plants, swamp forests, swamp shrub and bushes, and peatland forests. Other wetland agricultural plants actually produce the largest CO_2 emissions per hectare. Other wetland agricultural plants referred to here are all plantation and agricultural plants other

53

Table 1. Carbon emissions from wetland fires and carbon recovery rate

No.	Wetland Vegetation Types	Carbon Emission (Mg/ha)			Carbon Recovery Rate (Mg/ha/month)		
		Minimum	Maximum	Mean	Minimum	Maximum	Mean
1	Swamp Shrub and Bushes	57.92	195.39	155.76	4.64	23.73	17.35
2	Swamp Grass	24.64	165.85	73.75	0.91	20.04	7.73
3	Swamp Forests	146.47	167.13	156.44	7.41	15.16	11.52
4	Peat Swamps	0.17	44.39	16.59	0.59	14.61	7.10
5	Peatland Shrub and Bushes	70.66	179.92	136.24	4.24	22.24	14.38
6	Peatland Forests	115.85	157.29	137.59	0.44	5.93	2.89
7	Rice Fields	74.85	159.16	126.52	7.89	19.77	14.35
8	Wetland Plantations	105.48	158.81	133.11	1.52	8.77	5.49
9	Other Wetland Agricultural Plants	128.41	185.89	159.41	13.99	21.60	18.47
10	All Wetland Vegetation	0.17	195.39	121.61	0.44	23.73	13.12

Table 2. CO_2 emissions from wetland fires and CO_2 sequestration per month

No.	Wetland Vegetation Types	CO_2 Emission (Mg/ha)			CO_2 Sequestration (Mg/ha/month)		
		Minimum	Maximum	Mean	Minimum	Maximum	Mean
1	Swamp Shrub and Bushes	212.36	716.45	571.10	17.01	87.00	63.60
2	Swamp Grass	90.34	608.11	270.42	3.35	73.47	28.35
3	Swamp Forests	537.06	612.80	573.63	27.15	55.60	42.22
4	Peat Swamps	0.62	162.75	60.85	2.16	53.58	26.04
5	Peatland Shrub and Bushes	259.08	659.72	499.56	15.55	81.54	52.71
6	Peatland Forests	424.79	576.73	504.51	1.62	21.73	10.60
7	Rice Fields	274.45	583.58	463.90	28.94	72.48	52.62
8	Wetland Plantations	386.77	582.29	488.08	5.57	32.15	20.11
9	Other Wetland Agricultural Plants	470.84	681.59	584.51	51.31	79.21	67.74
10	All Wetland Vegetation	0.62	716.45	445.90	1.62	87.00	48.09

than rubber plantations and oil palm plantations. Rubber and oil palm plantations, whose emissions are not as high as other wetland agricultural plants, included in the wetland plantations class.
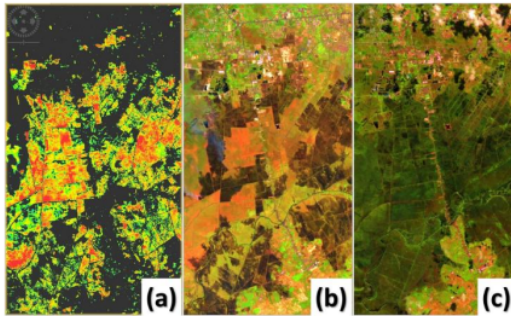

Figure 4. (a) Burned area from RBR, (b) Burned area on postfires imagery, and (c) Regrowth imagery

The result of extracting burned area automatically using RBR was shown in Figure 4. The result of extracting burned area automatically using RBR actually has one drawback. That was, when green vegetation dries up, even if it has not burned, it was detected as a burned area. This is because the RBR algorithm uses chlorophyll-sensitive NIR channels (green vegetation). Therefore, when vegetation loses chlorophyll, either by burning, cutting down or land cleared, or even just dried, it will be identified as burned. Thus, in appointing the samples in this study, visual justification was also involved. This was to distinguish which areas had been actually burned, and which areas had not been actually burned but were detected as burning.

Even though other wetland agricultural plants and swamp shrubs and bushes produce the largest CO_2 emissions for the average size per hectare, as shown in Table 2 and Figure 5, these two types of wetland vegetation require a relatively short time to recover to their condition back to the time before the fire (Table 3). Table 3 showed that

other wetland agricultural plants only need about 9 months to recover their biomass or carbon stocks as before. Meanwhile, swamp shrubs and bushes need a relatively little longer time, that is 8 months to one year to get recovered.
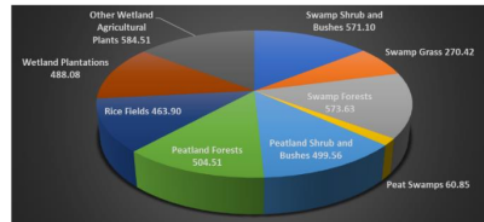

Figure 5. Average CO_2 emissions per hectare due to fires in each wetland vegetation

DISCUSSION

One of the recommendations generated from the Workshop on Tropical Wetland Ecosystems of Indonesia is, remotely sensed determinations of landuse and landcover change supported by ground-truth data should be extensively used to reduce current uncertainties in quantifying the extent and carbon stock changes in tropical wetlands (Murdiyarso et al., 2012). Even though there is no direct field measurement in this research, the AGB estimation model used in this research was developed based on ground truth. Indeed, in the future it is necessary to conduct further studies on the use of remote sensing technology supported by field data in order to estimate the total biomass, not only AGB as in this research. Given that fires in tropical wetlands, particularly on peatlands, do not only occur above ground but also in peat soils. In fact, underground fires on peatlands can emit more than 100 Mg/ha of carbon (Sirin et al., 2021).

Ballhorn et al. (2009) reported carbon emissions from fires throughout Indonesia in 2006 was 0.25 Giga tons, from an area of 1,331,367 hectares. This means that carbon emissions resulting from peatland fires were around 187

55

Table 3. The length of time for wetland carbon recovery to return to its original vegetation state

No.	Wetland Vegetation Types	Fastest carbon recovery time (months)	Longest carbon recovery time (months)	Average carbon recovery time (months)	Recovery Methods
1	Swamp Shrub and Bushes	8.24	12.48	8.98	Natural
2	Swamp Grass	8.28	26.98	9.54	Natural
3	Swamp Forests	11.02	19.78	13.59	Natural
4	Peat Swamps	0.29	3.04	2.34	Natural
5	Peatland Shrub and Bushes	8.09	16.66	9.48	Natural
6	Peatland Forests	26.54	261.60	47.59	Natural
7	Rice Fields	8.05	9.48	8.82	Cultivation
8	Wetland Plantations	18.11	69.45	24.27	Cultivation
9	Other Wetland Agricultural Plants	8.61	9.18	8.63	Cultivation
10	All Wetland Vegetation	0.38	8.24	9.27	Natural and cultivation

Mg/ha, or equivalent to 685.67 Mg/ha CO_2. Mg/ha or equivalent to 685.67 Mg/ha CO_2.

While Vásquez et al. (2020) estimates that CO_2 emissions from peat combustion in wildfires on Indonesian peatlands are 842 Mg/ha. These figures are more than we estimated in this research. Where in this research, peatland forests are estimated to emit only 504.51 Mg/ha of CO_2 gas into the atmosphere, as shown in Table 2. This can be understood because in this research we are only limited to measuring carbon emissions from aboveground fires, not to underground fires.

The results of this research show that overall, fires in tropical wetlands produce CO_2 emissions of 445.9 Mg/ha on average.

Sometimes it is difficult for us to imagine, the mass of 445.9 tons of carbon dioxide is how big it is. It would be easier to imagine it in terms of volume. The carbon dioxide gas emission units can be converted from mass units to volume units. According to the International Carbon Bank and Exchange (https://www.icbe.com), the formula for converting a mass of CO_2 gas into a volume of CO_2 gas is as follows:

Volume of CO_2 gas (m^3)
= Mass of CO_2 gas (Mg) x 22.73 moles x 24.47 L /mole

From Table 2, we can see that overall tropical wetland fires produce CO_2 emissions of 445.9 Mg/ha on average. If we convert this quantity to volume, the result will look like this:

$$Volume\ of\ CO_2\ gas\ (m^3)$$
$$= 445.9\ x\ 22.73\ x\ 24.47$$
$$= 248,010.96\ m^3/ha$$

The results of the conversion into volume units show that tropical wetland fires produce CO_2 emissions of 248,010.96 m^3/ha. A sphere with a diameter of 10 meters will have a volume of about 105 m^3. So that the volume of CO_2 248,010.96 m^3 is equivalent to 2,362 gas spheres with a diameter of 10 meters each. Imagining in the real world there are 2,362 gas spheres with a diameter of 10 meters each, released into the air during wetland fires might sound a little awful. Of course, this is only a prediction and measurement approach. Furthermore, the release of CO_2 emissions does not occur simultaneously at the same time, but takes place gradually throughout the process of fires.

Overall, as shown in Table 3, wetland vegetation takes an average of more than 9 months to recover its carbon stocks. Some of the vegetation will recover naturally, and some will be restored through cultivation, as well as agricultural land. Wetland vegetation that takes a long time to recover its carbon stocks are swamp forests and peatland forests. Swamp forests take a maximum of about 20 months, or an average of more than 1 year, to recover. What is quite worrying based on the results of this research are peatland forests, which on average take almost 48 months or 4 years to recover. And a maximum of more than 260 months or almost 22 years to restore the carbon stock back to its original state. Of course, what is meant here is above ground carbon. We can fully understand why swamp forests and peatland forests need a long time to recover the biomass, considering that both types of wetland vegetation are dominated by trees.

Wetland plantations referred to in this research are rubber plantations and oil palm plantations. Wetland plantations take about 1.5 to almost 6 years to recover to their initial biomass after burning. The time span is quite long, this is because the rubber plantations or oil palm plantations that are burned are at various stages of growth. If the burned rubber or oil palm is a young plant, it may only take about a year to recover. However, plants that are mature enough of course need a long time to recover as before. Based on the appearance of the burned area in the Sentinel-2imagery, most of the rubber plantations and oil palm plantations that were burned were still small plants or newly planted plants. This is of course considering that mature rubber or oil palm plants will get extra care from their garden owners so they don't burn. Furthermore, for wetland vegetation such as wetland plantations, swamp forests, or peatland forests, it is possible that only understorey plants or shrub and bushes may be burned under the stands.

The fastest recovery of carbon stocks came from peat swamps and rice fields. Considering that both types of vegetation or landcover are dominated by herbaceous plants, with very few woody plants. What needs to be understood is that peat swamps and rice fields have actually been emitting carbon into the atmosphere since the swamps began to dry up, even though the plants have not been burned. Especially for rice fields, the recovery is human cultivation. At the research site, the rice planting season generally takes place from February to April for each year. Considering that the regrowth imagery used in this research was acquired in May, the rice fields have recovered, even though the plants are not yet mature. That is why in this research, rice fields are estimated to take an average of more than 8 months to recover their carbon stocks.

CONCLUSSIONS

In general, tropical wetlands produce carbon emissions of 121.61 Mg/ha, or the equivalent to 445.9 Mg/ha of CO_2 gas. Wetland vegetation that produces the largest carbon emissions are other wetland agricultural plants, swamp forests, swamp shrubs and bushes, and peatland forests. Tropical wetlands take an average of more than 9 months to recover their carbon stocks. Peat swamps, rice

fields, swamp shrubs and bushes, and other wetland agricultural plant, require a fairly short time to restore their carbon stocks to their original state when they were not burned. Wetland vegetation types that take a long time to recover are swamp forests and peatland forests. Peatland forests take about 2 to 22 years to be able to restore carbon stocks, and this is only to restore carbon stocks above the ground surface. Because the carbon stock below the ground surface is beyond the scope of this research. In the future, a more comprehensive study may be needed to assess the total carbon emissions from wetland fires. Furthermore, because the method implemented in this research is completely based on remote sensing technology, of course, this method is able to simultaneously provide information over a very wide area and in a very efficient way.

ACKNOWLEGEMENTS

REFERENCES

Askar, Nuthammachot, N., Phairuang,W., Wicaksono, P., and Sayektiningsih, T. 2018. Estimating Aboveground Biomass on Private Forest Using Sentinel-2 Imagery. Journal of Sensors 2018: Article ID 6745629, 11 pages.

Ballhorn, U., Siegert, F., Mason, M., and Limin, S. 2009. Derivation of burn scar depths and estimation of carbon emissions with LIDAR in Indonesian peatlands. Proceedings of the National Academy of Sciences of the United States of America 106 (50): 21213-21218.

BPS-Statistics of Kalimantan Selatan Province. 2021. Kalimantan Selatan Province in Figures 2021. Banjarbaru: Badan Pusat Statistik Provinsi Kalimantan Selatan.

Chen, B., Yun, T., Ma, J., Kou, W., Li, H., Yang, C., Xiao, X., Zhang, X., Sun, R., Xie, G., and Wu, Z. 2020. High-Precision Stand Age Data Facilitate the Estimation of Rubber Plantation Biomass: A Case Study of Hainan Island, China. Remote Sensing 12 (23): 385.

Chen, Y., Guerschman, J., Shendryk, Y., Henry, D., and Harrison, M. T. 2021. Estimating Pasture Biomass Using Sentinel-2 Imagery and Machine Learning. Remote Sensing 13 (4): 603.

Delegido, J., Verrelst, J., Alonso, L., and Moreno,J. 2011. Evaluation of Sentinel-2 Red-Edge Bands for Empirical Estimation of Green LAI and Chlorophyll Content. Sensors 11 (7): 7063-7081.

European Space Agency. 2012. Sentinel-2: ESA's Optical High-Resolution Mission for GMES Operational Services (ESA SP-1322/2 March 2012). Noordwijk: ESA Communications.

Fang, P., Yan, N., Wei, P., Zhao, Y., and Zhang, X. 2021. Aboveground Biomass Mapping of Crops Supported by Improved CASA Model and Sentinel-2 Multispectral Imagery. Remote Sensing 13 (14): 2755.

He, L., Wang, R., Mostovoy, G., Liu, J., Chen, J. M., Shang, J., Liu, J., McNairn, H., and Powers, J. 2021. Crop Biomass Mapping Based on Ecosystem Modeling at Regional Scale Using High Resolution Sentinel-2 Data. Remote Sensing 13 (4): 806.

Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., and Ferreira, L. G. 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sensing of Environment 83: 195-213.

Imanudin, M. S., Wildayana, E., and Armanto, M. E. 2018. Option for Land and Water Management to Prevent Fire in Peat Land Areas of Sumatera, Indonesia. Journal of Wetlands Environmental Management 6 (1): 12-26.

Imran, A. B., Khan, K., Ali, N., Ahmad, N., Ali, A., and Shah, K. 2020. Narrow band based and broadband derived vegetation indices using

Sentinel-2 Imagery to estimate vegetation biomass. Global Journal of Environmental Science and Management 6 (1): 97-108.

Key, C. and Benson, N. 2005. Landscape Assessment: Remote Sensing of Severity, the Normalized Burn Ratio; and Ground Measure of Severity, the Composite Burn Index, In FIREMON: Fire Effects Monitoring and Inventory System, RMRS-GTR, Ogden, UT: USDA Forest Service, Rocky Mountain Research Station.

Koutsias, N. and Karteris, M. 2000. Burned area mapping using logistic regression modeling of a single post-fire Landsat-5 Thematic Mapper image. International Journal of Remote Sensing 21: 673-687.

Kumar, P., Krishna, A. P., Rasmussen, T. M., and Pal, M. K. 2021. An Approach for Fraction of Vegetation Cover Estimation in Forest Above-Ground Biomass Assessment Using Sentinel-2 Images. International Conference on Computer Vision and Image Processing (CVIP) 2020: 1-11.

Kumar, P., Krishna, A. P., Rasmussen, T. M., and Pal, M. K. 2021. Rapid Evaluation and Validation Method of Above Ground Forest Biomass Estimation Using Optical Remote Sensing in Tundi Reserved Forest Area, India. ISPRS International Journal of Geo-Information 10 (1): 29.

Lehner, B. and Doell, P. 2004. Development and Validation of a Global Database of Lakes, Reservoirs and Wetlands. Journal of Hydrology 296 (1-4): 1-22.

Li, C., Zhou, L., and Xu, W. 2021. Estimating Aboveground Biomass Using Sentinel-2 MSI Data and Ensemble Algorithms for Grassland in the Shengjin Lake Wetland, China. Remote Sensing 13 (8): 1595.

Lopez Garcia, M. and Caselles, V. 1991. Mapping Burns and Natural Reforestation using Thematic Mapper Data. Geocarto International 6: 31-37.

Ma, S., He, F., Tian, D., Zou, D., Yan, Z., Yang, Y., Zhou, T., Huang, K., Shen, H., and Fang, J. 2018. Variations and determinants of carbon content in plants: a global synthesis. Biogeosciences 15: 693-702.

Murdiyarso, D., Kauffman, J.B., Warren, M., Pramova, E. and Hergoualc'h, K. 2012, Tropical wetlands for climate change adaptation and mitigation: Science and policy imperatives with special reference to Indonesia. Working Paper 91. CIFOR, Bogor, Indonesia.

Naik, P., Dalponte, M., and Bruzzone, L. 2021. Prediction of Forest Aboveground Biomass Using Multitemporal Multispectral Remote Sensing Data. Remote Sensing 13 (7): 1282.

Otsu, N. 1979. A Threshold Selection Method from Gray-level Histograms. IEEE Transactions on Systems, Man, and Cybernetics 9: 62-69.

Pang, H., Zhang, A., Kang, X., He, N., and Dong, G. 2020. Estimation of the Grassland Aboveground Biomass of the Inner Mongolia Plateau Using the Simulated Spectra of Sentinel-2 Images. Remote Sensing 12 (24): 4155.

Parks, S. A., Dillon, G. K., and Miller, C. 2014. A New Metric for Quantifying Burn Severity: The Relativized Burn Ratio. Remote Sensing 6, 1827-1844.

Qi, J., Chehbouni, A., Huete, A.R., Kerr, Y.H., and Sorooshian, S. 1994. A modified soil adjusted vegetation index. Remote Sensing of Environment 48, 119-126.

Sirin, A., Maslov, A., Makarov, D., Gulbe, Y., and Joosten, H. 2021. Assessing Wood and Soil Carbon Losses from a Forest-Peat Fire in the Boreo-Nemoral Zone. Forests 12, 880.

Syam'ani. 2020. Capability of Sentinel-1 Synthetic Aperture Radar polarimetric change detection for burned area extraction in South Kalimantan, Indonesia. IOP Conference Series: Earth and Environmental Science 500: 012004.

Torabzadeh, H., Moradi, M., and Fatehi, F. 2019. Estimating Aboveground Biomass in Zagros Forest, Iran, using Sentinel-2 Data. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-4/W18, GeoSpatial Conference 2019, 12–14 October 2019, Karaj, Iran.

Vásquez, R., Benoist, A., Roda, J.-M., and Fortin, M. 2021. Estimating greenhouse gas emissions from peat combustion in wildfires on Indonesian peatlands, and their uncertainty. Global Biogeochemical Cycles 35: e2019GB006218.

Vuorinne, I., Heiskanen, J., and Pellikka, P. K. E. 2021. Assessing Leaf Biomass of Agave sisalana Using Sentinel-2 Vegetation Indices. Remote Sensing 13, 233.

Remote Sensing-Based Assessment of How Much Tropical Wetland Fires Contribute to Carbon Emissions and How Fast the Carbon Recovering Is