PARAMETERS TO ESTIMATE CO_2 EMISSION IN PEATLAND AREA BASED ON CARBON CONTENT AND SUBSIDENCE RATE FROM SAR INTERFEROMETRY

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ABSTRACT:

Peatlands are one of the important parameters to determine environmental quality because peatlands can store carbon stocks in their biomass. Based on the official page pantaugambut.id, Kalimantan Island is the second largest area that has peatlands. Land subsidence (subsidence) on peatland is one of the physical environmental impacts due to the shrinking volume of peat due to the drought process at a certain level in peatland processing, but also due to the decomposition process, erosion, and peat fires. This subsidence phenomenon will be measured using the InSAR technique, which is one of the existing methods in active remote sensing technology to measure changes in the earth's surface which is calculated based on changes in the phase difference between two SAR image acquisitions. Our research used the time series InSAR technique with the incorporation of Persistent Scatterer (PS) and small baseline approach to accurately calculate the value of soil subsidence rate to the cm-mm level. Furthermore, the estimation of CO_2 emission was calculated from the carbon parameters observed by the in-situ measurement, the affected peatland area, and its subsidence obtained by satellite remote sensing. We found that the highest CO_2 emission was located in the southern part of the study area. Since years ago, the region has been affected by deforestation and land expansion due to the need for fiscal revenues from palm oil and urbanization.

1. INTRODUCTION

Peatlands are one of the important parameters to determine environmental quality because peatlands can store carbon stocks in their biomass. Based on the official page pantaugambut.id, Kalimantan Island is the second largest area that has peatlands. Land subsidence (subsidence) on peatland is one of the physical environmental impacts due to the shrinking volume of peat due to the drought process at a certain level in peatland processing, but also due to the decomposition process, erosion, and peat fires. Dradjat et al. (1986) and Rina and Noorginayuwati (2007) reported a subsidence rate of 0.36 cm/month in the sapric peat soil of Barambai (South Borneo) for 12-21 months after reclamation, while for the sapric peat in Talio (Central Borneo) the rate was 0.178 cm/month and 0,9 cm/month for the hemic peat. Land subsidence in Babat Raya and Kolam Kanan Villages, Barambai District, South Borneo suffered from subsidence about 75-100 cm for 18 years (April 1978- September 1996) (Widyati, 2011).

Carbon storage in peatlands has been found in organic materials that make up peat, plant tissue, and litter (Widyati, 2011). Based on previous research, Indonesia has around 21 million ha of peatland with the below-ground carbon storage of approximately 37 gigatonnes (Gt) (Wahyunto et al., 2000). Peatlands are a huge store of carbon. Stored carbon could be released into the atmosphere due to land clearing activities. Logging accompanied by fire will accelerate the process of biomass emission. Thus, the carbon contained in peat soil is unstable. When peat forest is cleared and drained, the carbon stored will easily decompose and produce CO_2. In addition, excessive peatland drainage will make peatlands vulnerable to fires. Fires can reduce carbon storage in plant tissue and in peat. CO_2 emissions are a product of the oxidation-reduction process of organic matter from peat and are the largest contributor to greenhouse gas emissions. The decomposition, consolidation (compacting), and fires cause peat will experience subsidence and loss of various functions in supporting the surrounding land from flooding and drought. Namely, the conversion of peatlands due to land clearing activities causes an increased rate of C emissions. According to Hooijer et al. (2010), it is estimated that emissions associated with changes in peatland use and peatland management give 50% of Indonesia's national emissions.

Therefore, the calculation of peat carbon emissions aims to determine the amount of CO_2 released into the atmosphere due to the decomposition of peat organic matter or land clearing activities (fire; logging; drainage; addition of fertilizers) which affects the volume of peat. The amounts of emissions from peat soils over a period of time can be calculated based on the changes in carbon stored in peat soil. For this reason, an MRV (measurable, reportable, and verifiable) system of measuring and monitoring carbon emissions and peatland subsidence is necessary. Estimating carbon emissions requires two components which are activity data and emission factors. Activity data is the change in land cover over several periods, obtained through a radar approach while emission factors are the values obtained from the in-situ measurement and the constant conversion from C to CO_2 (IPCC, 2006).

InSAR is a technique in radar remote sensing to measure deformation in the earth's surface which is calculated based on

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the change in phase difference between two SAR image acquisitions (Zebker and Werner, 1994). Some previous research has been proved InSAR as an effective technique to monitor subsidence not only in urban areas (Aobpaet et al., 2013) but also in peatlands (Hoyt et al., 2020; Khakim et al., 2020; Umarhadi et al., 2022). Peatlands in neighbor regions were monitored by measuring differences in water table depth (Hooijer et al., 2012; Nusantara et al., 2018). However, peat subsidence in South Kalimantan has not yet been extensively studied by either tracking of water table depth or geodetic techniques such as leveling, GNSS observation, and InSAR.

With the study area located in several areas of South Kalimantan, the research has strategically used the advanced InSAR technique, namely Persistent Scatterer (PS) InSAR (Crosetto et al., 2016) with the integration of small baseline approach (Hooper, 2008) to accurately calculate the value of peat subsidence to the cm-mm level. Furthermore, CO_2 emission would be estimated based on the integration of in-situ measurements and the time series InSAR analysis.

2. METHODOLOGY

2.1 The study area

The research project was located both in Banjar Regency and Banjarbaru City, South Kalimantan, Indonesia shown in Figure 1. Peatland ecosystems had been existed in the regency even there was one of the districts name after the abundant peat soil, Kecamatan Gambut. Banjar Regency had an area of 4,668.50 km^2 and consisted of 20 districts. The altitude of it was a range between 0 and 1,878 m from the mean sea level. Mostly, the land use was dominated by the national forest with an area of 86,510 ha (Bappeda, 2013).

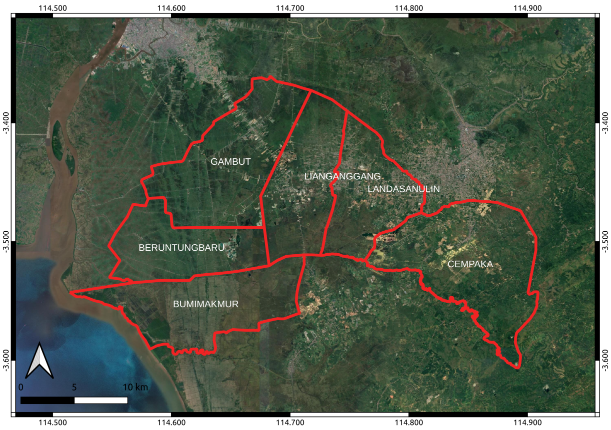

Figure 1. Location of the study area in Banjar Regency and Banjarbaru City, South Kalimantan, Indonesia. Source of satellite images: Google Earth

2.2 Parameters to estimate CO_2 emission

Considering the two previous sub-sections, we furtherly can estimate CO_2 emission using those parameters and additional supporting data. The relationship between CO_2 gas emission monitoring and water depth was discussed by Hooijer et al. (2010) and Zhou et al. (2016) and used in this study to calculate CO_2 emission from water depth change which can be expressed as follows:

$$CO_2\,emission = area \times WT \times CO_2 1m(t/y) \qquad (1)$$

and a modification into:

$$CO_2\,emission = 3.67 \times area \times WT \times Cm(t/y) \times P \qquad (2)$$

with $CO_2 1m(t/y)$ = 3.67 × C m
WT = peat subsidence rate (cm/y) / XO
Cm = carbon content × peat bulk density × XO

where 3.67 = the conversion factor from C to CO_2
$area$ = drained or burned area within peatland area (ha)
WT = average groundwater depth change in the study area (cm/y)
Cm = C loss at an average groundwater depth of 1m (t C/ha/y)
XO = the coefficient of the linear relationship between subsidence and water table change
P = the percentage of C released as CO_2

Further detail regarding the formulas can be read from Dahdal (2011). Since the unavailability of water table change data in the study area, we assumed that XO the coefficient value of water table change and subsidence rate is $\sim$ 0.04 - 0.1 (Wösten et al., 1997; Wösten and Ritzema, 2001). However, it was eliminated in the extended calculation due to a relationship between WT and C_m. For the percentage of P, we used 100% in a condition that all carbon loss was converted into CO_2 and methane emissions were negligible. Another option can be taken from a 92% oxidation of the total subsidence for peatlands drained over 18 years which was used for estimating the CO_2 emission rate by Hooijer et al. (2012). The formula to estimate CO_2 finally can be calculated as follows:

$$\begin{aligned} CO_2\,emission = 3.67 \times area \times peat\ subsidence\ rate \\ \times\, carbon\ content \times peat\ bulk\ density \times P \end{aligned} \qquad (3)$$

According to equation (3), the estimation of CO_2 can be calculated based on the parameters generated by in-situ and InSAR observation. Figure 2 shows an illustration of parameters needed to estimate CO_2 emission. Carbon content and peat bulk density were collected from ground in-situ measurement in Banjar Regency and its surroundings while peat subsidence rate can be continuously monitored by the space-borne time series InSAR technique, namely radar remote sensing. Since the map of the peatland area was unavailable in the study area, we used another alternative to solve this issue. The land cover can be classified based on optics remote sensing as substitution data finding how much the area of peatland is. We processed the image classification from Landsat-8 to generate a peatland area in South Kalimantan.

2.3 The time series InSAR method

We utilized an archive of multi-temporal Sentinel-1 SAR images from January 2019 to February 2021. 66 Descending SLC images from VV polarization with the area of interest in South Kalimantan, Indonesia. The path, frame, and absolute orbit of the selected C-band image were 105, 601, and 26077, respectively. An external digital elevation model from SRTM 1 arcsecond was used to minimize the error from the topography effect.

233 interferograms were generated based on the time series InSAR algorithm, Persistent Scatterer with Slowly Decorrelated

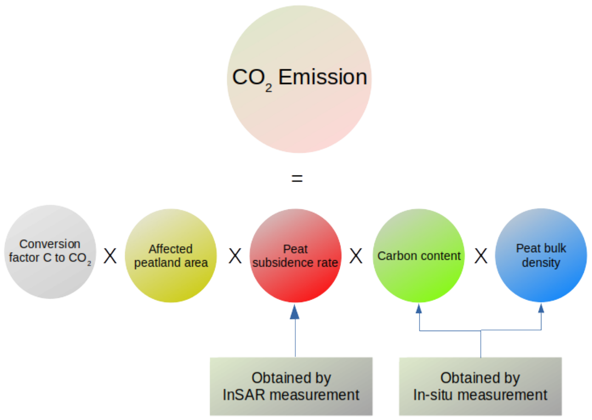

Figure 2. An illustration of parameters needed to estimate CO_2 emission based on InSAR and In-situ surveying data.

Filtered Phase (SDFP) (Hooper et al., 2004; Hooper, 2008). The configuration of SDFP was mainly developed from the small baseline method (Berardino et al., 2002; Schmidt and Buergmann, 2003) with an improvement to consider characteristics of stable phase within multi-master and slave pairs. The technique mostly was known as incorporation between the PS and Small Baseline Subset (SBAS) approach. To avoid decorrelated signals due to surface characteristics mostly covered by soils and vegetation, we performed the network pairs with a perpendicular baseline of 100 m and a temporal baseline of 50 days. Figure 3 shows the result of the small baseline configuration used in the research of peatland subsidence monitoring.

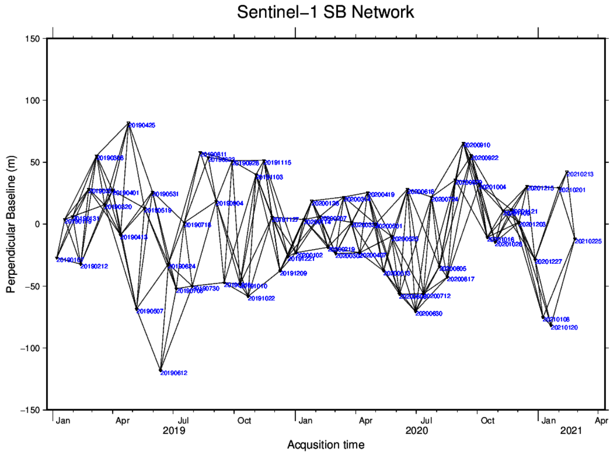

Figure 3. The small baseline network was created to process the time series InSAR technique with the PS-SDFP algorithm

The InSAR processing was generally divided into two main steps. The first step was an interferometric chain in which SLC images were firstly coregistered to a super master image and continued to range and azimuth filtering (Hanssen, 2001). Interferogram formation was performed with multi pairs created from the small baseline network and the differential InSAR was executed using SRTM data. Furthermore, we identified the candidate of PS with amplitude difference dispersion (ADD) with a threshold less than 0.6. The wrapped product of interferograms was analyzed with the phase stability estimation and SDFP pixels selection. The final PS points subsequently were 3D unwrapped (Hooper and Zebker, 2007) to the original value of 2ϕ cycles and the unwanted signals due to other effects such as the spatially look angle error, the digital elevation model (DEM) error, the atmospheric artifact, and the orbital error was reduced. The last procedure was an inversion of displacements from the small baseline to single master mode using the Gauss–Markov theorem. Finally, the time series displacement was generated and the subsidence rate can be determined from the PS distribution of mean velocity in the observed study areas.

2.4 In-situ measurement of carbon content

The parameters used in the calculation of carbon stock are peat area, peat soil depth, bulk density (BD), and carbon content (C-organic/C-org) in each peat sampling area. Peat soil sampling in measuring peat depth and carbon content (C-org) using the Eijkelkamp peat drill, consisting of a peat sampler, 5-9 extension rods, and one pair of handles. Meanwhile, BD is calculated from soil samples taken with a ring sampler. BD of peat was determined in the laboratory by the gravimetric method.

While the determination of the C content by the loss on ignition method, all organic matter present in the soil sample was burned at 5500C for 6 hours. Burned organic matter will evaporate and the remaining material is inorganic material such as soil clay, grains of dust, and fine sand. The weight loss of oven-dried soil samples in combustion is the weight of organic matter. The conversion from the weight of organic matter to the weight of C-org uses a factor of 1/1,724. This method is semi-quantitative because the weight loss during the ash process only describes the organic matter content. The conversion factor of 1/1,724 is a general number of the relationship between organic matter and carbon (Agus, 2009; Agus et al., 2011).

3. RESULT AND DISCUSSION

The results are divided into the InSAR observation and in-situ measurement. The first sub-section concerns explain the subsidence rate that occurred in Banjar Regency and its surrounding where mostly peatland soil surfaced on the bare land region. The next sub-section describes the extraction parameters of carbon content that were useful to estimate CO_2 emission. They were taken directly from in-situ measurements held twice to find the information of bulk density, depth of peatland, and a total of C organic. Then, we estimated CO_2 emission based on the generated parameters in the study area.

3.1 Subsidence rate in peatland area observed by the time series InSAR

The PS-SDFP technique was used to detect subsidence in Banjar Regency and its surrounding. Although the detected signal of surface displacement can not be distinguished directly between peatland and non-peatland regions, we presented generally the subsidence that occurred in the study area.

Figure 4 shows the rate of the line of sight (LOS) displacement within 39 and -45 mm/year. The south region was more impacted by subsidence than the north region. The maximum subsidence rate in the most southern area can reach -45 mm/year but the northern area had a general rate of -15 mm/year. We also detected uplift areas (the blue color) and assumed that the cause could be the effect of anthropogenic activities such as a new residential development, atmospheric artifacts, or noise that cannot be eliminated in the time series InSAR processing. Another reason was the imperfect removal of phase residual (Fattahi and Amelung, 2013) due to an inaccurate external DEM to define man-made objects in this suspected area.

We plotted some samples of time series displacement distributed in the stable and deformed areas. As shown in Figure 5, Point 1 (114.7235991^o,-3.4282887^o) was located in the sub-urban land use and belonged to the stable area. Since the land use was for human settlements, the area did not cover with peat soil. Point 2 (114.687122^o,-3.517750^o) was located in the southwest of the study area, Landasan Ulin Selatan, close to TS5 and TS6 points (Figure 6). Point 3 (114.750508^o,-3.501066^o) was located in the southeast of the study area, Sambangan, near TS29 and TS30. Point 4 (114.707546^o,-3.379838^o) was located at the northern part of the study area, Pematang Panjang, close to TS11 and TS12 while point 5 (114.702434^o,-3.417620^o) was located in Landasan Ulin Barat near to TS25 and TS26. In order to avoid a misinterpretation of the displacement trend, two SAR scenes on 03 March 2020 and 25 February 2021 were eliminated in the time series displacement since we found the phase jump as the presence of spike noise.

The area of point 3 was the highest subsidence rate in Banjar Regency while point 2 was the second-highest rate. The area of point 2 was mostly covered by wetland vegetation with the land use of cultivated land. Based on the ground investigation, some were former burn areas and the rest has mostly changed to arable land for oil palm plantations. Furthermore, the land use of point 3 was bare land prepared for the expansion of residential housing. We found that this region barely surfaced by peat wetlands. Meanwhile, in the north part which was the location of points 4 and 5, the regions were mainly untouched by anthropogenic activities (e.g. deforestation, urbanization, and land degradation).

3.2 Carbon content from in-situ data

The result of laboratory analysis for soil samples collected in the in-situ surveys is presented in Table 1. 17 samplings have been successfully extracted to measure carbon content in Banjar Regency. The Bulk Density range for peat is generally around 0.02 – 0.3 t/m3 depending on its maturity, density of the peat, and the level of inorganic matter. For all points except TS2 and TS3, the bulk density was more than 0.65 because the peat soil was scarcely found from the collected samples. Moreover, the percent total organic C is still in the range of peat C org content, they are 18-58% if the analysis uses the loss on ignition method.

The carbon content of peatland was calculated from BD and C organic total extracted from soil materials of 17 sample points. The result of carbon content approximately was around 9 - 44 t/m^3 distributed in Banjar Regency and Banjarbaru City. Figure 7 shows a clear picture of peat soils found in the in-situ point of TS13. It was located in drained peatland near the region of Landasan Ulin Selatan. Table 1 shows the carbon content of 17 areas sampling about 0.1-0.3 t/m3. Page et al. (2002) suggested an average carbon content volume (Cv) value of peatland is 0.06 t/m3. However, based on observations from hundreds of peat samples from Sumatra and Kalimantan (Agus et al., 2011), the Cv value cannot be the same for each site. The value differences are determined by the level of peat maturity. Cv ranged from 0.082±0.035 t/m3 is classified as sapric, 0.057±0.026 as hemic, and 0.046±0.025 t/m3 as fibric. The homogeneity of Cv values could result in large errors in the estimation of emissions and carbon stocks based on a subsidence value.

Sample Codes	Bulk Density g/cm^3)	C organic total (%)	Carbon Content (t/m^3)	Depth of Peat (cm)
TS1	0.601	52.60	0.316	15
TS2	0.694	54.21	0.376	15
TS3	0.713	55.42	0.395	12
TS4	0.661	50.00	0.331	1
TS5	0.446	54.36	0.243	12
TS6	0.570	54.15	0.309	10
TS11	0.227	46.07	0.104	72
TS12	0.166	49.71	0.082	220
TS13	0.496	53.19	0.264	12
TS15	0.251	53.24	0.133	16
TS16	0.274	51.76	0.142	10
TS17	0.245	52.81	0.129	11
TS18	0.337	54.27	0.183	9
TS25	0.473	47.93	0.227	9
TS26	0.164	49.06	0.008	21
TS29	0.305	52.93	0.161	18
TS30	0.324	53.71	0.174	16

Table 1. Carbon content parameters of peatland extracted by in-situ surveys in Banjar Regency and Banjarbaru City, South Kalimantan, Indonesia.

The relationship between subsidence rate and the depth of peatland can clearly show that the higher the value of subsidence, the thinner the depth of peat soil. Point 4 (TS11 and TS12) presented the northern part of the observed area was a primary forest hence peat soils were abundant proved by the depth of peat soils until 220 cm. On the other hand, the southern part (points 2 and 3) has been involved in human activities that harmed natural resources, especially in peatland areas. Deforestation and land degradation have been occurred in the highest subsidence rate areas where the original primary forest altered to oil palm plantations and development of residential housing. These areas mostly had the depth of peat soil with a range between 1 and 21 cm.

Drainage peatlands (Figure 7) caused by land-use change in need of oil palm cultivation lead to a decrease of the peat depth in time and oxidation for half of the carbon stored in Indonesia. It can be deduced CO$_2$ emission increase of 6.5 ppm in case of drainage for peat extraction (Siegert and Jaenicke, 2008).

Since the reduction of carbon stocks in peatland is related to subsidence, it influences the sustainability of agricultural business in peatlands. The use of peatlands for agriculture needs to consider sustainability and environmental aspects. For the reason of peatlands used for agriculture, a sustainable peat management system must be applied. Considering the relatively low productivity of peatlands and the important role of peatlands as a buffer for environmental quality, it is necessary to try to minimize the use of peatlands for land development.

3.3 Estimation of CO$_2$ emission using the available data

Considering a limit number of in-situ measurements, CO$_2$ emission would be provided by two scenarios; a) point-wise estimation from the available in-situ data and InSAR and b) an interpolation grid of in-situ points using the IDW method overlayed by both the affected peatland area and peat subsidence.

Firstly, Table 2 presents the result of CO$_2$ emission based on point-wise in-situ data. The drained and burned area is assumed to be equal to the spatial resolution of the InSAR result which is 30 m x 30 m. A significant subsidence rate is considered as the loss of carbon stored in peatland and produced CO$_2$ emission

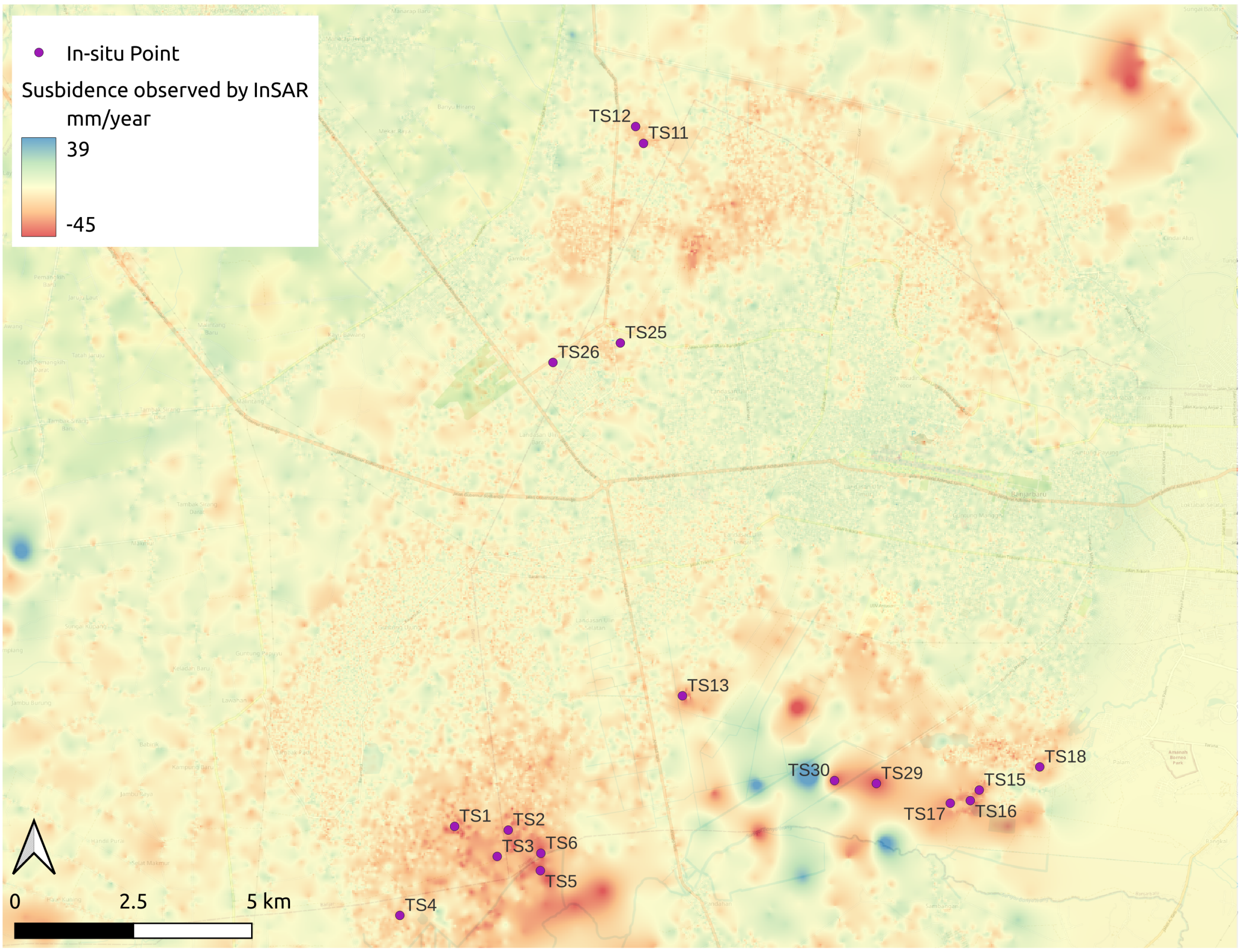

Figure 4. Map of subsidence rate in Banjar Regency and Banjarbaru City, South Kalimantan, Indonesia and its surroundings observed by Sentinel-1 Descending SAR data from 2019 to 2020.

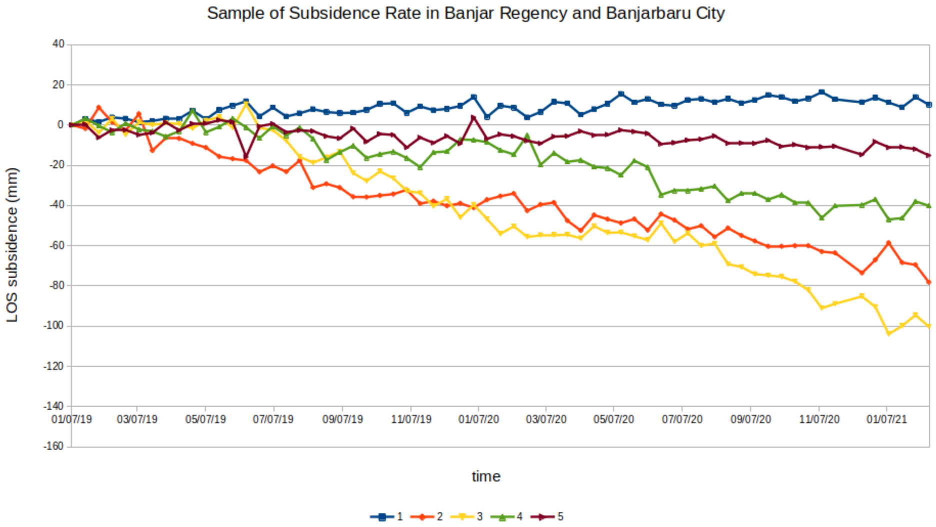

Figure 5. Sample of the time series InSAR results in Banjar Regency and Banjarbaru City, South Kalimantan, Indonesia.

which is calculated by multiplying the subsidence rate by the peat bulk density and carbon content.

For the second scenario, the map was generated by the interpolation grid of bulk density and carbon content from in-situ measurement points, then subsidence rate map from InSAR, as well as peatland area data in the study area were obtained from the supervised classification method based on Landsat-8 optical

Figure 6. The field documentation was located at the point of TS5 and TS6. The in situ data was collected along a stream where part of the small peat deposits was visible and the access was relatively easy.

Figure 7. A picture of peat soils found in drainage peatlands, Landasan Ulin Selatan, Banjarbaru City, Indonesia.

remote sensing. Figure 8 shows the value of CO_2 emissions in the range of 0 - 0.364tC ha^{-1} yr^{-1}. It also has a large land subsidence rate of -47.34 mm/yr. The southern part of the study area tends to have a higher value of CO_2 emissions than the northern part, as in point 26 there is a peatland area that has the lowest emission of 0.00001 tC ha^{-1} yr-1. The total area of peatland suffered by land subsidence of 4,636.98 ha is estimated to have a total CO_2 emission of 1.699 tC ha^{-1} yr^{-1}.

Regarding a complete oxidation process, we computed the percentage of C released as CO_2 of 100%. It means that carbon loss because of peat subsidence fully contributed to carbon dioxide emissions in the study area. Our result found that the highest CO_2 emission from peat oxidation of 0.27 tC ha^{-1} yr^{-1} or to be exactly 3.02 CO_2/year/0.09 ha located in the southwest study area, namely Kecamatan Liang Anggang, Banjarbaru City near TS 3 and 6.

Estimation of carbon emissions based on subsidence according to Wösten et al. (1997), assuming no fires occur, contributes to 60% of subsidence value while compaction is 40%. In contrast, Couwenberg et al. (2010) reported that the peat decomposition process resulted in 40% in subsidence value. For example, in TS1, the subsidence rate is 30.99 mm/y, which means 12.39 mm contributed from peatland decomposition and the rest 18.6 mm made by consolidation.

Sample Codes	Area (ha)	Peat subsidence rate (mm/yr)	P (%)	CO_2 ems (t C ha^{-1} yr^{-1})
TS1	0.09	-30.99	100	0.19
TS2	0.09	-27.11	100	0.23
TS3	0.09	-29.19	100	0.27
TS4	0.09	-22.37	100	0.16
TS5	0.09	-41.85	100	0.15
TS6	0.09	-42.35	100	0.25
TS11	0.09	-11.14	100	0.01
TS12	0.09	-13.34	100	0.01
TS13	0.09	-25.07	100	0.11
TS15	0.09	-26.15	100	0.03
TS16	0.09	-21.6	100	0.03
TS17	0.09	-35.06	100	0.04
TS18	0.09	-26.8	100	0.05
TS25	0.09	1.02	100	0
TS26	0.09	-6.066	100	0
TS29	0.09	-45.98	100	0.07
TS30	0.09	-47.32	100	0.09

Table 2. Estimation of CO_2 emissions (ems) based on point-wise in-situ data in Banjar Regency and Banjarbaru City, South Kalimantan

Various factors affect the rate of peat decomposition, which affects the rate of emission too. Emission rates can be different depending on peat maturity classified based on the stage of decomposition, fertilization, and the influence of plant root respiration. The highest peat maturity classified as sapric, based on a percent of organic matter value, is located on TS 11, 12, 25, and 26. The rate decomposition of organic matter in that sites is mostly humified with the C organic of 48.90 (Agus et al., 2011). It made the subsidence rate and the emission rate is lower too than the others, especially in TS 25, 26 the emission rate of 0.4 and 0.29 t.C/ ha/year, respectively.

4. CONCLUSION

We performed a process of space-borne InSAR method to determine the area of subsidence in the peatland regions of South Kalimantan, Indonesia. A campaign of in-situ surveys was done in purpose to get the information of carbon storage in the chosen sample areas. The observation of SAR interferometry and in-situ data can be used to estimate CO_2 emission implementing the association between the area of peatland that was drained or burned, peat subsidence rate, the peat bulk density, and carbon content.

Further development of our research would be a mapping of CO_2 emission regionally in Banjar Regency, Banjarbaru City, and other areas in South Kalimantan. Moreover, we would like to increase in-situ measurements regularly and add monitoring of water table depths as a validation of the subsidence rate derived by radar remote sensing data.

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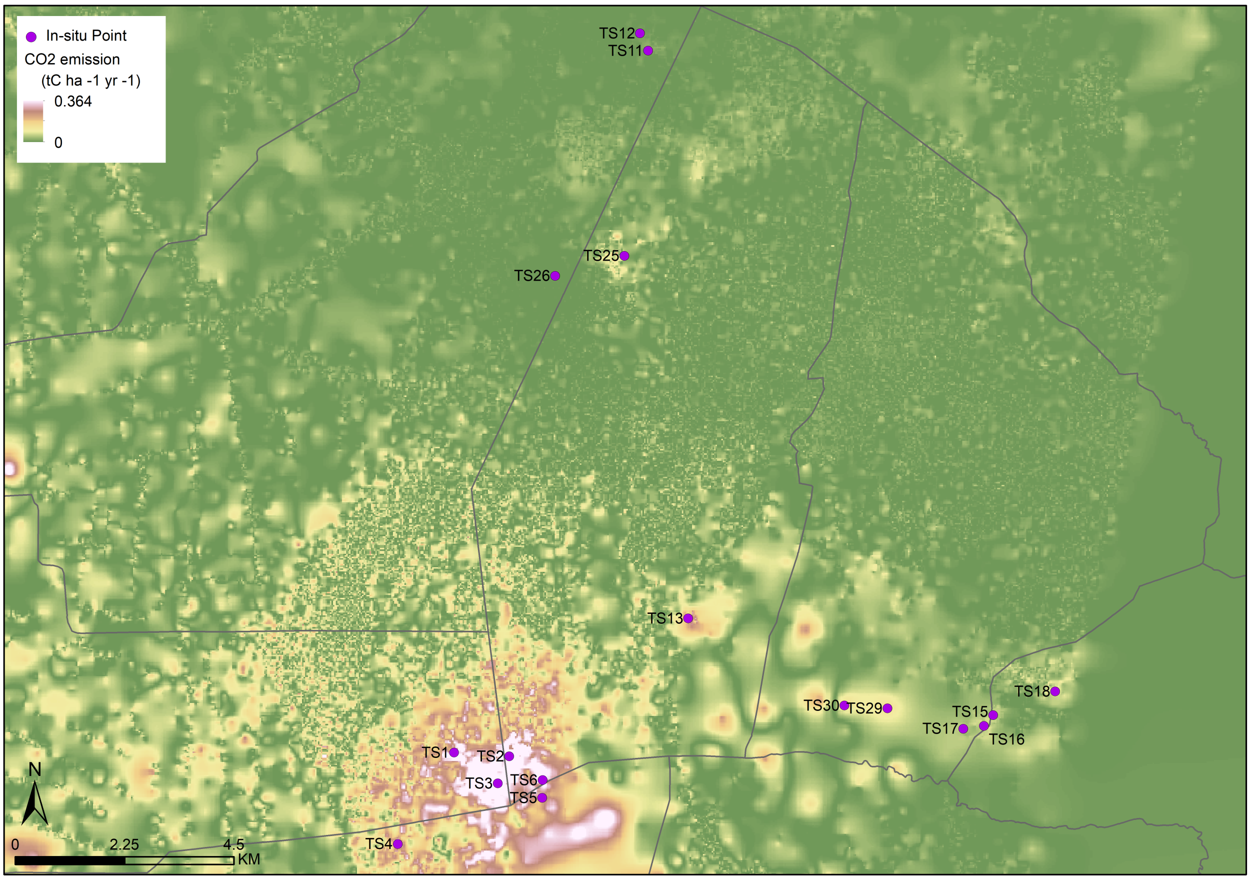

Figure 8. A map of CO2 emission in Banjar Regency and Banjarbaru City, South Kalimantan, Indonesia estimated by the in-situ measurement and satellite remote sensing.

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