BIODIVERSITAS
Volume 23, Number 12, December 2022
Pages: 6539-6545

ISSN: 1412-033X
E-ISSN: 2085-4722
DOI: 10.13057/biodiv/d231252

The partial contribution of CO_2-emission losses from subsidence in small-holder oil palm plantation on a tropical peatland in West Kalimantan, Indonesia

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Manuscript received: 21 July 2022. Revision accepted: 16 December 2022.

Abstract. *Astiani D, Widiastuti T, Ekamawanti HA, Ekyastuti W, Roslinda E, Mujiman. 2022. The partial contribution of CO_2-emission losses from subsidence in small-holder oil palm plantation on a tropical peatland in West Kalimantan, Indonesia. Biodiversitas 23: 6539-6545.* Carbon storage in tropical peat ecosystems over thousands of years, especially within peat soil, is in huge quantity. Degradation of peat ecosystems is generally caused by human factors, whether intentional or not, damaging the carbon storage function of tropical peatlands, where forest clearing, drainage development, and burning of land converted to agriculture and plantations result in significant greenhouse gas emissions. Tropical peat in the Kubu Raya District of West Kalimantan, which has a relatively large area of peat, has been degraded as a cause of uncontrolled drainage and land fires caused by a lack of management after its forest cover was lost. The main impact is an increase in peat CO_2 emissions due to changes in land use, especially lowering groundwater levels. Subsequently, the subsidence process also occurs after land clearing. This study aims to obtain the proportion of carbon biomass loss due to the CO_2 emission process from reducing the peat layer due to subsidence. Data collection was executed for two years, where CO_2 emission was monitored bi-weekly, and the subsidence was measured bi-monthly. The results demonstrate groundwater levels dictate the peat CO_2 emission and subsidence. Lowering GWL 30 to -85 cm increases CO_2 by more than three times, approximately. The rate of peat subsidence shows similar trends to the emission. The proportion of peat biomass loss on CO_2 emission was between 58.9 to 73.5%, except for GWL ~5 cm, where the proportion was the highest at 82%. The results of this study are beneficial in explaining the part of the subsidence that impacts the sources of CO_2 emissions from the small-holder oil palm and GWL management on peatlands.

Keywords: CO_2 emission, hydrological management, peatland drainage, small-holder oil palm plantation, subsidence

INTRODUCTION

Tropical peatlands are one of the essential water-logged global sinks of atmospheric carbon dioxide (CO_2) and have accumulated at least 100 Gt carbon (Dommain et al. 2011; Xu et al. 2018). The Indonesian archipelago, especially Papua, Sumatra, and Kalimantan, is a large island rich in soil carbon since around 21 Mha of tropical peatland is distributed in these areas. Tropical peatlands cover approximately 10% (or 1.7Mha) of West Kalimantan land, 40% of which is peat swamp forest at various levels of forest degradation, and the rest has been converted into other land uses and land cover areas (Miettinen et al. 2011). Several studies showed that tropical peatlands are considered threatened ecosystems, mostly due to human activities and development (Rieley et al. 2016; Roucoux et al. 2017; Dargie et al. 2019)

In recent years, changes in land cover, from peatland forests to small and large plantations, have changed the carbon balance of peatlands (Astiani et al. 2015; Hatano 2019). Moreover, these plantations construct canals in the peatlands to lower the water level and allow plant roots to grow. As a result, these activities change the dynamics and flux of carbon on peatlands (Astiani et al. 2015; 2016) and increase carbon emission (Miettinen et al. 2017; Wijedasa et al. 2018; Cook et al. 2018; Manning et al. 2019). In addition, drainage development on peatland exposes peat carbon to the aerobic condition that enhances decomposition, resulting in millions of tons of carbon loss every year (Carlson et al. 2012; Hirano et al. 2012). It is confirmed that lowering groundwater level increase peat oxidation, convert organic matter accumulated below the peat layer to CO_2, and increase land subsidence (Hoyt et al. 2020).

Peatlands in Indonesia store around 13.6-40.5 to 55-61 Gigaton C of carbon (Siegert and Jaenicke 2008; Warren et al. 2017). Within a smaller unit, per one-meter depth, peat stores 600 tons of C ha^{-1} for Fibrist and reaches 1,500 tons of C ha-1 for relatively mature peat in West Kalimantan and Central Kalimantan (Astiani et al. 2016; Siregar & Narendra 2021). Furthermore, in an open peatland, decompose rate is 19-75 tons ha annually. The decomposition process runs slower by 6-25 tons $ha^{-1}y^{-1}$ in less degraded peat swamp forests Astiani (2017). Carbon above the peat surface accumulates 0.5 to 1.0 mm, while, on the other hand, drained peat losses 1.5-3.0 cm per year.

About 50% of decreasing peat layer occurs due to oxidation (Wosten et al. 1997). Because the subsidence rate is 15-30 times the accumulation rate on dry peat, peatlands exposed to deforestation can be a significant source of greenhouse gas emissions.

Total soil respiration consists of autotrophic and heterotrophic components. Heterotrophic respiration only involves microbial decomposition of soil organic matter (SOM), resulting in CO_2 emission from peat soil, whereas autotrophic respiration includes root growth and maintenance (Hergoualc'h et al. 2017). Kubu Raya District in West Kalimantan covered the largest peat area in the Province (~4,2 x 10^5 ha). Due to development pressures, there have been changes in land uses and covers that impact changes in the balance and dynamics of carbon - loss of biomass or land degradation impact on managing land on peat. The impact of peatland drainage causes irreversible surface subsidence due to reduced peat thickness or subsidence, partly due to biological oxidation and another due to condensation or drifting in the form of dissolved organic carbon and particulate organic carbon resulting in loss of carbon stocks. Understanding the consequences of land cover changes on peat, usually measured from the depth of subsidence, consists of a decomposition process in the form of loss of CO_2 and compaction of the peat soil. Therefore, studying the proportion of subsidence lost in the form of CO_2 emissions due to heterotrophic respiration is necessary for carbon losses to be better estimated.

MATERIALS AND METHODS

Study area

The study was carried out on an area of small-holder oil palm in Kuala Dua Village, Kubu Raya Regency, West Kalimantan Province. The landscape of this location has been encountered by the construction of drainage canals, which were built in 2008-2009. Unfortunately, the water level was not regulated, and it was only in 2019 that simple dams were built for research purposes. Before the groundwater level (GWL) was set up at study sites, the water levels varied at an average of 85 cm. In several small spots, this land has been planted by local farmers with oil palm plants and some agricultural products. Still, due to the relatively dry condition of the peat, agricultural business in this area did not produce good results. The research was carried out for 24 (twenty-four) months; however, the GWL ~0 cm was conducted only for 12 months; during this period, almost the entire oil palm land for this study was GWL-set up. The setup was conducted to regulate several GWLs. However, within two years of study, we observed GWL fluctuation due to rainfall variability in this ombrogenous peatland.

The study was accomplished on a small-holder oil palm on peatland, which also found fern ground covered and other shrubs within an area of ~6 ha. The soil respiration assessment and peat soil from the area were collected within various environmental conditions, especially the groundwater level. Several tools for taking data were undisturbed soil samples, a peat drill (Russian Borer) LICOR-8100 CO_2 soil respiration measurement tool that assessed the overall respiration from peat soil, a subsidence measurement tool, water level monitoring tool (HOBO level meter), temperature and humidity measuring instrument.

Data collection

Data assessed directly in the field includes biweekly CO_2 respiration data, monthly subsidence data, and 30-minute uploaded water level data. In addition, other environmental data such as temperature, peat soil moisture, and peat water content at the study sites. Data analyzed in the laboratory included the water content of the peat, dry peat weight and peat bulk density, ash content, and soil pH.

Measurement of heterotrophic respiration from peatlands

The measurement of heterotrophic respiration or CO_2 emission follows the measurement method used by Astiani et al. (2018). Carbon dioxide emissions are obtained partially from the amount of CO_2 respiration from peat soils. The proportion of CO_2 emission (heterotrophic respiration) to total respiration for oil palm has not been widely tested, but the estimation of the proportion of heterotrophs respiration or CO_2 emissions follows Melling (2013).

Carbon dioxide respiration was measured using a Li-Cor 8100 Automated soil CO_2 flux system (IRGA, Li-Cor 8100, Li-Cor Inc. Lincoln, Nebraska 68504, USA) or a similar device using a 20 cm diameter collar made of PVC, which is placed permanently on peat soil. The collars are placed 10 cm into the soil and 2 cm above the soil surface and then connected to Li-Cor 8100-102 soil flux Survey Chamber. Li-Cor 8100 contains an infrared gas analyzer for measuring CO_2 and H_2O concentrations.

Table 1. Study site description for spatial site location, land history, peat depth, peat-sample depth, and mean annual precipitation

Information	Description
Site coordinate	0013’ S, 1090 26’ E
Land history	Burned for plantation past 5-6 yr, drainage
Peat depth	3.6-4.1m
Soil samples depth	0.0-0.4m
Rainfall quantity (mm y-1) in last 5 years	3122mm ± 376mm

Respiration of CO_2 from the soil was measured twice per month and assessed more intensively in the dry season months (July-September 2020-2021), for dry and wet months, to ascertain the effect of this water level on reducing emissions from peatlands. Based on the results of preliminary measurement data, the daily mean CO_2 respiration in tropical peat can be represented effectively by measuring the minimum (6:00-8:00) and maximum (12:00-14:00) daily respiration (Figure 2). Then the results are averaged to get the daily CO_2 respiration rate. Along with the CO_2 emission assessment, some site conditions, such as soil humidity, ambient CO_2 concentration, vapor concentration, and soil temperature, were also recorded.

Even though we noticed significant CO_2 emission results with the water level treatment carried out, from the evaluation along the measurement times, the variations in ground cover and conditions on the oil palm inspection paths and among sites are pretty varied. Therefore, the measurement sampling was added to represent land conditions better. In addition, the placement of soil collars was scattered over the location with 15 replications, 3 of each groundwater table set up.

Subsidence measurement

At all subsidence measurement locations, the alternation of the peat surface level was monitored by using a 5 cm diameter hollow PVC rod inserted vertically through the peat and up to at least 0.5 m in the mineral substrate at the peat bottom. A permanent marker and a thin metal pre-border mark were assigned on the peat surface (Figure 2). The 'anthropological' compaction of peat surface was prevented by ensuring that field personnel did not stride within a 0.5 m radius around the PVC stick sites and tread only on the planks that were kept during installation. Monthly measurements were made over the study period of up to two years.

Subsidence measurements in the small-holder oil palm lands were carried out at 15 points, where the measurement points were grouped into 5 clusters based on the water level in the landscape. The measurement sites were ± 30 cm, ± 40 cm, ± 50 cm, and ± 60 cm, and one site in a non-regulated water table (~85 cm), where each cluster has three measuring points. In addition, three assessment points were established on approximately water-log sites close to the oil palm site after one year of study for non-drainage peat site comparison.

Data analysis

The analysis of the amount of emission and subsidence was presented in a simple table form, and the results of the measurement of the groundwater level were presented in terms of mean and standard deviation. Some of the measured site factors will be presented as daily averages. The statistical analyses and graphical presentation were run using SigmaPlot 12.5

Figure 1. Emission measurement on peatland using the portable Licor-8100

Figure 3. Illustration of measurement of subsidence in small-holder oil palm on peatlands

RESULTS AND DISCUSSION

CO_2 emission in small-holder oil palm on peatland

The results of CO_2 emission from oxidative respiration measurements show that the water table level in the peat landscape, combined with other site factors (i.e. soil temperature, soil humidity), plays an essential role in determining the amount of CO_2 emission from peatlands. Water level depth and soil moisture are critical environmental parameters that affect soil storage and carbon loss from tropical peat ecosystems (Hirano et al. 2012). Water level depth is determined by rainfall, evapotranspiration, and discharge, influencing soil moisture throughout the soil column and controlling, to some extent, soil respiration across tropical peatlands (Morris 2021). That also occurs in various types of land cover when the water level falls far below the surface soil and soil respiration increases, such as in oil palm and forest areas (Swails et al. 2019).

The water level depth of > 80 cm increased sharply by more than three times compared to the peatland GWL 30 cm (Figure 4). In the oil palm land with GWL 30 cm, the mean CO_2 emission was 32.8 t CO_2 ha^{-1} $year^{-1}$ while the water level ranged from >80 cm to average emitting 102,1 ton CO_2 ha^{-1} $year^{-1}$. As a comparison, in wet peatland with approximately GWL ~5 cm, the mean CO_2 emission rate shows the lowest at 18,5 ton CO_2 ha^{-1} $year^{-1.}$ and inflating with decreasing GWL. Peat water table levels consistently play a role in CO_2 emissions from these lands. These results, consistent with Hirano et al. 2014), mentioned that overall soil respiration decreased as GWL lowered due to the vertical distribution of oxidative respiration that shifted downward with the expansion of an unsaturated soil zone. Further analysis shows a significant correlation between GWL and CO_2 emission in this peatland.

Subsidence in small-holder oil palm peatlands

Subsidence measurements were carried out on peatlands with water level variations based on the survey results and previous GWL mapping. Similar to the CO2 emissions rate, the subsidence rate also fluctuates at various water levels. The measurement results demonstrate that subsidence inpeatlands tends to increase with deeper GWL. Moreover, it fluctuates approximately at a similar rate monthly on each GWL. However, deeper levels such as GWL ≥85 cm show a higher rate in 2 years of assessments (Figure 5). These consistent subsidence results should not be taken for granted, where in long-term management, decreasing peatland carbon and also peat layer levels on peatland could be a devastating issue (Wijedasa et al. 2017)

In dryer peat conditions, the bi-monthly subsidence fluctuations were observed and increased (Figure 5). The GWL >85 cm shows the highest subsidence rate with 2-year accumulative subsidence of 14.4 cm, followed by GWL at 60 cm with 9.8 cm, a slower increase at 50 to 30 cm, respectively. At GWL 0-5 cm and sometimes inundation, subsidence is relatively slow.

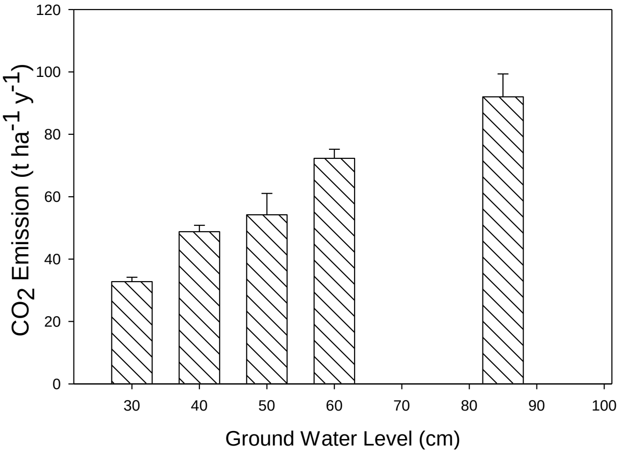

Figure 4. Distribution of heterotrophic respirations (CO_2 emission) in various GWLs in the study site

The amount of subsidence accumulation in peatlands in various ranges of GWL, with different subsidence at each groundwater level, is presented in Figure 6. These results indicate that the peatlands that are always wet have the least accumulation of subsidence and increase when GWL moves down below the soil surface. For example, Peatland with GWL 30, 40, 50, 60, and >85 cm consistently increased subsidence.

The occurrence of subsidence in peatland is explained as the compression of saturated peat below the water level due to loss of buoyancy from above the peat, adding to the strain on the peat below its water level (Hoogland et al. 2012). Primary consolidation is caused by loss of water from the pores in the peat; it occurs fast when groundwater is removed rapidly, especially where a tight drainage system is applied in high permeability peat.

The subsidence which occurs in open peatlands is indeed relatively lower (4.7 cm) per year on land with a GWL of around 80 cm, compared to recently cleared peatlands, such as the results of monitoring by Hoijier et al. (2012), where in the early years after development subsidence drainage or land subsidence in the first year after drainage, measured up to 60 to 90 cm. Until the 5th year, the total subsidence of peat occurs up to 140 cm. However, the following years slowed considerably because the peat soil became more stable. A mean reduction rate of 5 cm per year was found in Acacia and oil palm plantations more than five years after drainage. For comparisons, the subsidence rate of 28 years after drainage was 4.6 cm per year on an oil-palm plantation in Johor (Malaysia). With a steady water level average of 0.5 m, the subsidence means was 3.7 cm per year in 11 other locations (Wosten et al. 1997), while Anshari et al. (2021) found the subsidence was 2 and 6 cm in forest and degraded peatland consecutively.

The proportion of losses due to CO_2 emissions from subsidence

Although the subsidence measurement has only been carried out for two years, the portion of subsidence lost from CO_2 emissions can be estimated. It is indicated that not all part of subsidence is a loss in the form of CO_2 emission or through soil water flow within canal outlets. The previous measurement calculated the bulk density of peat in this area per cm of peat thickness ~21.41 CO_2 ton $ha^{-1}y^{-1}$. Based on the amount of CO_2 emissions in each GWL condition in the peatland, the loss of emissions can be converted into the thickness of the peat layer loss. Estimates of the proportion of peat layer loss from the subsidence magnitude are presented in Table 1.

Table 1 shows subsidence and CO_2 emissions increase accordingly as the GWL continues below ground level. Thus the proportion of losses due to heterotrophic oxidation also increases as the peat dries. What needs to be underlined is that in open peat areas, which are sometimes inundated with water, almost no or very little subsidence occurs. Although the amount is small, nearly all of the loss of peat biomass due to heterotrophic emission activity (~82%) reduces biomass in this open peatland. At higher GWL, the variation in the proportion of peat loss due to emissions is relatively narrower (59 to 74%, depending on GWL). It is demonstrated that the amount of emission and subsidence increases with the increase in GWL on these oil palm peatlands. Astiani et al. (2018) and Swails et al. (2019) showed that water level significantly affects CO_2 emissions in peatlands. Another result on peatland subsidence declared 1.55 to 1.62 cm yr^{-1}, of which oxidative peat decomposition mentioned a relatively equal range of 72 to 74% (Ishikura et al. 2018).

The results demonstrate that the peatland subsidence is not completely account for peat loss (Table 1). Hoijier et al. (2012) stated that the conversion of tropical peatlands to agriculture, as well as of degraded peatlands (Anshari et al. 2021), could lead to the release of carbon from previously stable long-term storage, resulting in subsidence of the soil surface which can be a substitute measure for CO_2 emissions to the atmosphere. However, the finding of this study shows that the proportion of carbon loss from tropical peatlands was not the actual loss of peat biomass as a whole.

The partial loss of peat biomass through oxidative peat decomposition varies depending on peatland GWL, especially on wet soils. On relatively moist peat soil (GWL ~0 to 5 cm), almost all of the decrease in peat surface occurs due to heterotrophic respiration/ emissions from peatlands (81.8%). However, the amount of CO_2 emitted is relatively low, 18.5 ton ha^{-1} y^{-1} at GWL ~0-10 cm compared to 102 ton ha^{-1} y^{-1} at GWL ~85 cm. At a 30-50cm water level, the proportion of loss due to heterotrophic respiration is smaller than the lower GWL >50 cm. Yet, all lowering GWL has the chance to solidify because the cavity previously filled with water becomes empty and filled with air so that, over time, it becomes compacted. It is supported by peat bulk density on each GWL depth (0.16, 0.18, and 0.22 g cm^{-3} consecutively for GWL 30, 50, and ~85 cm). It indicates an increase in bulk density with lowering groundwater levels from the peat surface. Likewise, on drier peat soils, the proportion is relatively similar, but the rate of oxidative peat decomposition increases. The estimation of carbon loss through CO_2 emissions must also consider the condition of the peat landscape's groundwater level. The proportion of peat biomass loss due to peat CO_2 emission from the results of this study might detail the subsidence data, which is usually more available, and show actual peat losses in a peat area unit.

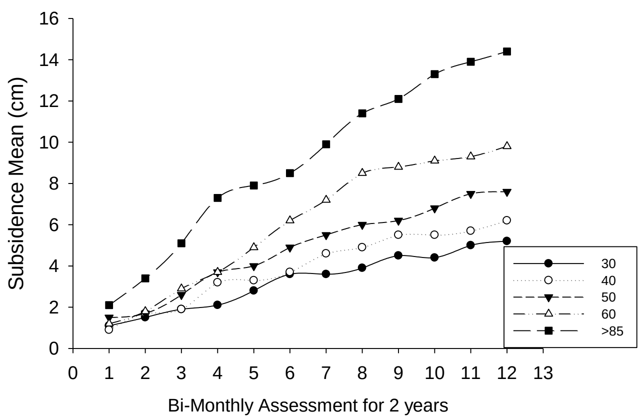

Figure 5. Bi-monthly fluctuation of accumulated subsidence in small-holder oil palm on peatland at various groundwater levels

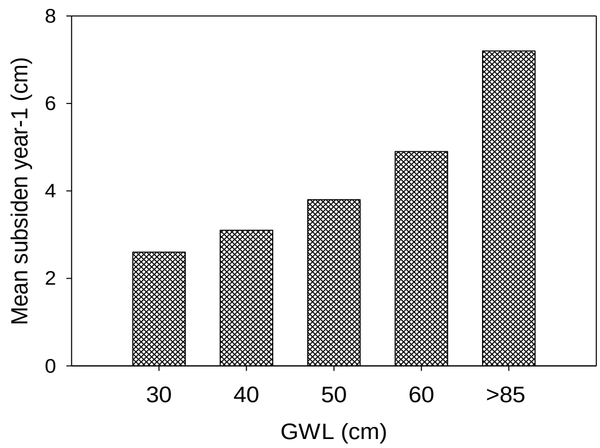

Figure 6. Accumulated annual subsidence means of two years assessments demonstrate higher CO_2 emission with deeper GWL

Table 2. The estimated proportion of peat loss by emissions from the rate of subsidence in small-holder oil palm plantations on peatlands

Water level set up (cm)	Mean actual water level on OP plantation (cm)	Accumulate subsidence for 2 years (cm)	Mean annual subsidence (cm)	CO_2 emission (t ha^{-1} y^{-1})	Peat biomass loss on CO_2 emission (cm y^{-1})	% Loss in emission from the subsidence
0	5.2	-	1.1	18.5	0.9	81.8
30	31.6	5.2	2.6	32.8	1.5	58.9
40	42.3	6.2	3.1	48.8	2.3	73.5
50	55	7.6	3.8	54.2	2.5	66.6
60	61.4	9.8	4.9	72.3	3.4	68.9
>85 (TD)	87.4	14.4	7.2	102.0	4.8	66.7

Note: TD: Water level was not regulated

Another variable that may also play an important role in subsidence in small-holder oil palm on peatlands is carbon loss through water flows out of drainage with POC and DOC measurements. Our investigation previously indicated that some carbon continuously moves through water flow in canals surrounding areas. The three years of monthly-monitoring carbon losses in the form of POC and DOC of canal and ditches surrounding the area were 3,47 and 1,65 ton CO_2 y^{-1}, consecutively. These losses represent 2.2-6.2% TOC and 1.1%-3.1% DOC proportion of subsidence, which is relatively insignificant compared to CO_2 emission losses. Although the proportion of losses through water flow is relatively small, the canal's development and management should be set up not to increase the carbon loss from peat soil (e.g. to avoid large water head differences in canals and large discharge from peat hydrological units). Water level set up in small-holder oil palm peat areas is important in mitigating CO_2 emissions and continuously decreasing peat thickness.

The results of this study indicate that, together with other site factors such as soil and ambient temperature and moisture, GWL plays a role in determining the amount of heterotrophic respiration. Likewise, our other study results of monitoring subsidence in open peatlands show a similar trend, where the influence of GWL plays a role in the size of subsidence. However, the proportion of peat biomass losses through CO_2 emission is slightly lower (Astiani et al. in progress). Therefore, water management by maintaining groundwater levels around 30-40 cm would mitigate soil CO_2 emissions from oil palm plantations on tropical peatlands.

Integrating the measurement results of subsidence and the proportion of CO_2 emission concomitantly could explain the amount of carbon loss from the system. Furthermore, it provides baseline information to calculate the carbon budget, specifically from the soil in a natural landscape, which could immediately reduce peatland soil CO_2 emissions if there is an increase due to human activities and management changes on peatlands.

To prevent the loss from being overstated, the results of this study can be used to estimate the loss of soil peat biomass during a specific period, even if only subsidence data are available in some areas. It is advised to conduct more research in a peatland system similar to this one since data on the loss of peat biomass can also be obtained from the emission of N_2O and CH_4 gases. Our findings are based on chamber measurements of soil emissions and subsidence for a specific location, such as small-holder oil palm peatland. It led to the development of empirical connections between measured carbon loss and GWL. This relationship is point-based and depends on distinct site conditions based on observations from soil flux chambers and subsidence. The baseline data from this microsite investigation may be used to confirm that GWL has a sizable impact on soil CO_2 emissions. The findings, nevertheless, need to be more thorough and might not be sufficient to explain geographic variations in peat CO_2 emissions.

ACKNOWLEDGEMENTS

We greatly appreciate Universitas Tanjungpura, Pontianak, Indonesia, for providing modest research funding to support field data collection. Thank you to Hendra, Jamiat, and Ilham Pratama, graduates and current students from the Faculty of Forestry at Universitas Tanjungpura, who helped with the field sampling.

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