

CO₂ fluxes from drained tropical peatland used for oil palm plantation in relation to peat characteristics and crop age after planting

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Abstract. Gusmayanti E, Anshari GZ, Pramulya M, Ruliyansyah A. 2019. CO₂ fluxes from drained tropical peatland used for oil palm plantation in relation to peat characteristics and crop age after planting. *Biodiversitas* 20: 1650-1657. Large expansion of oil palm plantation on peatland has changed its important role for carbon sink into carbon source. Conversion of peat swamp forest with high carbon density into monoculture of oil palm has released significant amount of carbon into atmosphere, either carbon previously stored in forest biomass or carbon stored in peat organic matter. Drainage canal to artificially lower groundwater level as prerequisite for oil palm cultivation provides favorable condition for soil microbes activities in decomposing peat organic matter, resulting in the increase of CO₂ flux. The fluctuation of groundwater level and variation of environmental factors near the peat surface may regulate the rate of CO₂ released from the soil. We aimed to measure CO₂ fluxes from two sites of oil palm plantation with different peat characteristics and analyzed the correlation with groundwater level, soil temperature, air temperature, gravimetric water content, peat pH, oxidative reductive potential, and crop age. The measurement had been conducted from September 2016 to April 2017 in West Kalimantan, Indonesia using portable infrared gas analyzer EGM 4. In addition to soil sampling at the same time as the gas measurement, we collected soil samples for some peat characteristics analysis, consisting of bulk density, particle density, porosity, soil organic matter, ash content, carbon, and nitrogen content prior to CO₂ flux measurement. Our result shows that the difference of peat chemical characteristics between two sites has resulted in different CO₂ flux. Oil palm ages seemed to affect CO₂ flux by regulating microclimatic condition around crop canopy. Young oil palm with less dense canopy associated with high CO₂ flux. The soil temperature has positive correlation with CO₂ flux and groundwater level, but it has negative correlation with gravimetric water content. However, there was insignificant relationship between CO₂ fluxes and groundwater level unless the groundwater level reached more than 50 cm from the peat surface. It implies that CO₂ flux is a complex process influenced by many peatland characteristics and environmental factors, particularly when groundwater level is high or near to the surface.

Keywords: CO₂ flux, drained peatland, groundwater level, oil palm plantation

INTRODUCTION

Tropical peatland is a significant carbon pool. It is estimated 81.7-91.9 Gt of carbon stored in 44 Mha of tropical peatland or equivalent to 15-19% of global carbon stock (Page et al. 2011). A new assessment reported a higher estimation of tropical peatland covering about 58.7 Mha (equivalent to 12.7% of global peatland) and containing 119.2 Gt of carbon (Dargie et al. 2017; Leifeld and Menichetti 2018). Of this, 28-57 Gt of carbon is stored in Indonesia in over 14-20 Mha of peatland (Page et al. 2011; Ritung et al. 2011; Warren et al. 2017).

A large amount of carbon in peatlands is potentially released to the atmosphere. Many studies have reported that the expansion of oil palm plantation on peatlands is the major driver in accelerating carbon loss from tropical peatlands (Carlson et al. 2012; Dislich et al. 2017). It is estimated about 50% of peatland in Peninsular Malaysia, Sumatra and Borneo have been converted into industrial and smallholder plantation in 2015 with the majority (about 73% or about 3.1 million hectares) of these areas are oil palm plantation (Miettinen et al. 2016). In Indonesia, oil

palm plantation expansion occurred at an average rate of 450000 ha year⁻¹ during 1995-2015 (Austin et al. 2017). Kusin et al. (2017) estimated the conversion of tropical forest into oil palm plantation has resulted in greenhouse gas emission four times higher compared to non-forest land use converted to oil palm plantation. The conversion of one hectare of forest on peat releases over 1,300 tons of carbon dioxide equivalents during the first 25-year cycle of oil palm growth (Germer and Sauerborn 2008). In Riau province, CO₂ emission from the conversion of peatlands is estimated at 10.8 Gt CO₂ year⁻¹ during the 1990s to the 2000s (Ramdani and Hino 2013).

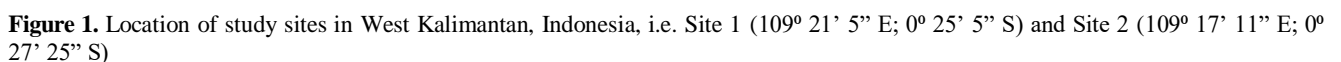
Drainage canal to drain excess water is a precondition for oil palm cultivation on peatland. Maintaining water level between 40-60 cm below the peat surface is recommended for optimal root growth due to oxygen availability for root respiration (Lim et al. 2012). The aerobic layer also provides a favorable condition for microbial activities in peat organic matter decomposition leading to high CO₂ emission (Astiani et al. 2018; Ishikura et al. 2018) and changed peatland role from a sink into a source of carbon (Miettinen et al. 2017).

In this study, we measured carbon fluxes from peatland used for oil palm plantation with different characteristics and analyzed the correlation between carbon flux and groundwater level, gravimetric water content, air and soil temperature, soil pH, and potential redox. Besides, we did correlation analysis between CO₂ flux and crop age.

Study area

1). Site 1 (109° 21' 5" E; 0° 25' 5" S) is a plantation covering about 15 thousand hectares, established in 2004. The plantation at site 2 (109° 17' 11" E; 0° 27' 25" S) has been established since 2008 with the total area is almost 9 thousand hectares. Planting space in both sites is 9m x 9 m in triangle pattern, hence there are 143 palms per ha or 4290 palms in a 30-ha block which is separated by drainage canal. The crop is regularly received fertilizers, particularly nitrogen, phosphorus and potassium.

We deployed four plots at each site. The plots were placed in between two crop lanes and had a size about 4m x 7m. The crop ages were 6-12 years after planting at Site 1, and 6-9 years after planting at Site 2. There were 6 measurement points in each plot, hence we had 48 measurement points in total and marked with collars (chamber bases) for CO₂ flux measurement. The layout of plot and measurement points are presented in Figure 2.



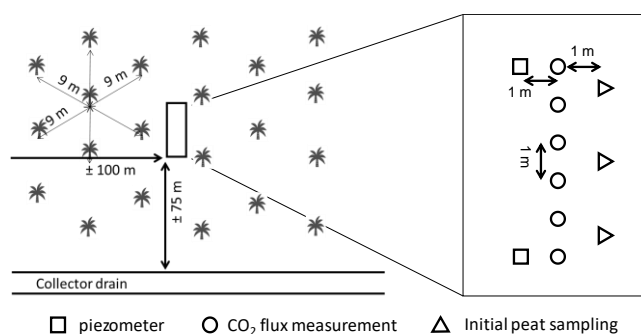


Figure 2. Layout of plots for CO₂ flux measurement, piezometer and peat sampling

CO₂ flux measurement and environmental variables as regulating factors

Carbon dioxide emission was measured every month from September 2016 until April 2017 using static closed chamber method. The apparatus consisted of Soil Respiration Chamber (SRC) and Soil Temperature Probe and the portable infrared gas analyzer called EGM 4 (<http://ppsyste.ms.com/egm-4/>). The gas analyzer measured the concentration of CO₂ within the chamber during the time of enclosure (about 2 minutes). The slope of linear regression between CO₂ concentration and time is converted into CO₂ flux.

Subplots as measurement points were deployed at the middle areas of cropping lanes to minimize exposure to agronomical related activities (Figure 2). The distance between two subplots was 1 m. The arrangement was also to minimize root respiration effect in CO₂ flux measurement (Dariah et al. 2014).

Other variables, i.e. air temperature, soil temperature, groundwater table, gravimetric soil water content, reductive oxidative potential, and soil pH, were measured monthly at the same time as the gas measurement. The air temperature was measured using a digital thermometer, while soil temperature was measured using a temperature probe of EGM 4. Groundwater table was manually measured using piezometer made from perforated PVC pipes of 2 inches diameter inserted about 1 m distance from the subplots. Gravimetric soil water content (in dry basis), oxidative reductive potential and soil pH were determined from soil sampled at the surface (0-10 cm).

Measurement of peat characteristics

Measurement of peat characteristics was conducted at the same time as the collar deployment. We collected peat soil samples using Eijkelpamp soil auger at three depths of 0-10, 10-20 and 20-30 cm for each measurement point (see Figure 2). There were three measurement points in each plot, hence there were 72 peat samples in total. The samples were taken to the laboratory for analyses to determine bulk density, particle density, porosity, organic matter content, ash content, organic carbon content and

nitrogen content. Bulk density, particle density and porosity were determined after oven drying at 105° for about 24 hours. Organic matter and ash content were calculated based on loss on ignition methods (as conducted by Satrio et al. 2009; Ywih et al. 2009). Carbon content and nitrogen content were determined by elemental analyzer as in Anshari et al. (2010). Peat depth was also determined by coring until the mineral substrate is found.

Data analysis

Statistical analysis of CO₂ flux data consisted of analysis of variances, statistical comparison, and correlation analysis. Data were grouped into sites, crop ages, and class of groundwater level for analysis of variances and pairwise comparison. Pearson correlation analysis between CO₂ flux data and environmental variables data was performed to measure the strength of the relationship among variables.

RESULTS AND DISCUSSION

Peat characteristics at the study sites

Study sites are located on peatland with different depths, ranged from 0.9 m (Site 2) to 4.7 m (Site 1). Peat at Site 2 is categorized as shallow peat (0.9-1.3 m), while at Site 1, peat is classed to deep peat (2.2-4.7 m). Physical characteristics of peat are not significantly different (*p*-value > 0.05) between the two sites (Table 1). Bulk density, particle density, and porosity ranged 0.07 g cm⁻³ (Site 1)-0.21 g cm⁻³ (site 2), 1.30 g cm⁻³ (site 2)-1.91 g cm⁻³ (site 1), and 85% (site 2)-96% (Site 1) respectively. These variables are significantly different between plots according to Brown-Forsythe ANOVA (*p*-value < 0.001, *p*-value = 0.034, and *p*-value < 0.001, respectively for bulk density, particle density and porosity).

Chemical characteristics of peat are found to be significantly different between Site 1 and Site 2. The *t*-test showed the *p*-value of soil organic matter, ash content, carbon, and nitrogen content are 0.002, 0.002, 0.028 and 0.044 respectively. Soil organic matter and ash content show the contrary pattern since the ash content is the remaining part after organic matter burnt from soil samples. Carbon content and soil organic matter have concordant results as the carbon is constituted within organic matter. The differences are detected as well among plots and crop age but are not significantly detected among different sampling depths, indicating the peat layer at 0-30 cm are relatively homogeneous.

CO₂ fluxes from oil palm plantation

Fluxes of CO₂ from two locations ranged from 0.13 to 1.23 g CO₂ m⁻² hour⁻¹ or equivalent to 11.8-107.4 ton CO₂ ha⁻¹ year⁻¹ (Figure 2). The average of CO₂ fluxes at Site 1 was 0.43 ± 0.18 g CO₂ m⁻² hour⁻¹ while CO₂ fluxes at Site 2 was 0.58 ± 0.24 g CO₂ m⁻² hour⁻¹. The differences are significant statistically according to *t*-test (*p*-value = 0.000).

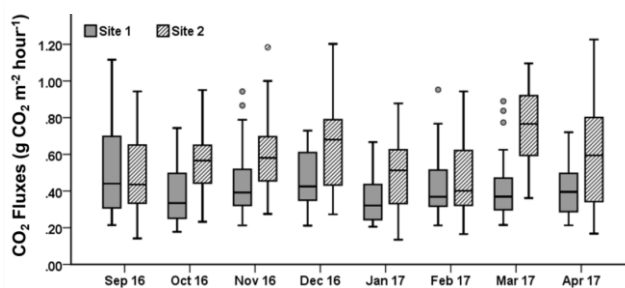
Table 1. Characteristics of peat at the study sites

Variables	Mean \pm standard deviation		
	Site 1 (n = 36)	Site 2 (n = 36)	Total (n = 72)
Peat depth (cm)	362 \pm 94	106 \pm 15	234 \pm 145
Bulk density (g cm ⁻³)	0.14 \pm 0.03	0.14 \pm 0.03	0.14 \pm 0.03
Particle density (g cm ⁻³)	1.49 \pm 0.10	1.45 \pm 0.11	1.47 \pm 0.11
Porosity (%)	90.71 \pm 2.37	90.25 \pm 2.38	90.48 \pm 2.37
Soil Organic Matter (%)	97.53 \pm 0.59a	94.80 \pm 4.92b	96.17 \pm 3.74
Ash content (%)	2.47 \pm 0.59b	5.20 \pm 4.92a	3.83 \pm 3.74
Organic carbon (%)	54.10 \pm 1.66a	52.10 \pm 1.66b	53.31 \pm 3.03
Total nitrogen (%)	1.92 \pm 0.22a	1.80 \pm 0.29b	1.86 \pm 0.26
ORP (Oxidative Reductive Potential, mV)	499.84 \pm 17.59	477.36 \pm 23.49	488.60 \pm 23.51
pH	3.26 \pm 0.11	3.29 \pm 0.25	3.28 \pm 0.19

Note: Different letter at the same rows indicates that the variables were significantly different according to t-test 5%

Table 2. Statistics of CO₂ flux and environmental variables as controlling factors at the study sites

Variables	N	Minimum	Maximum	Mean	Std. Deviation
<i>Site 1</i>					
CO ₂ Flux (Fc, g CO ₂ m ⁻² hour ⁻¹)	184	0.18	1.12	0.43	0.18
Soil Temperature (T _{soil} , °C)	184	27.0	34.3	28.7	1.2
Air Temperature (T _{air} , °C)	184	24.9	35.3	29.9	2.0
Groundwater Level (GWL, cm)	184	26	96	64	16
Gravimetric Water Content (GWC, %)	184	97	638	310	101
Oxidative Reductive Potential (ORP, mV)	184	340	571	466	39
Soil pH	184	3.01	4.08	3.42	0.24
<i>Site 2</i>					
CO ₂ Flux (Fc, g CO ₂ m ⁻² hour ⁻¹)	180	0.13	1.23	0.58	0.24
Soil Temperature (T _{soil} , °C)	180	25.6	34.4	28.3	1.0
Air Temperature (T _{air} , °C)	180	25.7	34.7	30.3	1.7
Groundwater Level (GWL, cm)	180	10	94	54	20
Gravimetric Water Content (GWC, %)	180	91	481	294	71
Oxidative Reductive Potential (ORP, mV)	180	140	554	432	75
Soil pH	180	2.92	4.99	3.50	0.36

**Figure 2.** CO₂ fluxes (g CO₂ m⁻² hour⁻¹) at the two sites of oil palm plantation during eight months measurement

Beside the peat characteristics, CO₂ flux is controlled by environmental factors. Table 2 presents environmental variables measured at the same time as CO₂ flux. During field measurement, air temperature ranged 24.9–35.3 °C, while soil temperature were 25.6–34.4 °C. Since these were instantaneous values, high-temperature records were due to direct sunlight reaching the open plots at the midday.

Groundwater level fluctuated from 10 cm–96 cm, averaged at 64 \pm 16 cm (Site 1) and 54 \pm 20 cm (Site 2). More than half of the total 364 data recorded groundwater level of more than 40 cm, a limit of groundwater level in government regulation for mitigation of CO₂ emission from peatlands. Gravimetric water content at peat surface (5–10 cm depth) were 91–638%, averaged at 310 \pm 110% (Site 1) and 294 \pm 71% (Site 2). Low water contents were recorded when groundwater levels were deep.

Correlation between CO₂ fluxes and environmental variables

CO₂ flux resulted from peat decomposition is a complex process involving microbial activities that are sensitive to environmental conditions. Relationships between CO₂ flux and these variables are graphically presented as scatter matrix (Figure 3). Interrelationship among variables depicted in the figure show the complexity of CO₂ flux process.

The correlation between CO₂ flux and soil temperature is statistically significant ($r = 0.166$; p -value = 0.002). The

correlation is higher in Site 1 ($r = 0.259$; p -value = 0.000) compared to Site 2 ($r = 0.245$; p -value = 0.001). Soil temperature effects on CO_2 fluxes are related to canopy cover of oil palm. In Site 1, we found strong negative relationship between soil temperature and oil palm age ($r = -0.347$; p -value = 0.000). Soil temperature of 9 years old oil palm is significantly higher than that of 12 years old oil palm at Games Howell test (p -value = 0.000) leading to significantly higher CO_2 flux at the 9 years old oil palm peatland (CO_2 flux = $0.60 \text{ gCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$) compared to the 12 years old oil palm peatland (CO_2 flux = $0.38 \text{ gCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$).

Our study also shows significant correlation of soil temperature with groundwater level ($r = 0.266$; p -value = 0.000) and gravimetric water content ($r = -0.167$; p -value = 0.001). When groundwater level is low or far from peat surface soil moisture of the aerobic layer decrease leading to the increase of soil temperature.

Air temperature and soil temperature are closely related. Similar to soil temperature, the correlation of air temperature with CO_2 flux is significant ($r = 0.221$; p -value = 0.000). It is also related to the canopy cover of oil palm. The crop canopy of 12 years oil palm seems to cause lower air temperature (29.4°C) than the canopy of 6 years old oil palm which result in 31.5°C of air temperature. As a result, the CO_2 flux of 12-year-old oil palm is lower ($0.38 \text{ gCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$) compared to the CO_2 flux of 6-year-old oil palm ($0.68 \text{ gCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$). We observed significant correlation between crop age with air temperature ($r = -0.252$) and soil temperature at site 1 ($r = -0.347$).

The relationship of CO_2 flux and groundwater level is not significant statistically ($r = -0.01$; p -value = 0.587). However, we detected positive correlation between CO_2 flux and groundwater level ($r = 0.217$; p -value = 0.001, $n = 241$) when groundwater level was lower than 50 cm (Table 3). The correlation was also found in Site 1 ($r = 0.260$; p -value = 0.000, $n = 184$) where the groundwater level averaged at $64 \pm 16 \text{ cm}$.

Our dataset shows there is no significant correlation between CO_2 flux and GWC. The pattern of GWC effect on CO_2 flux was inconsistent as some higher GWC data associated with lower CO_2 flux, while other data showed the contrary. However, our study observed positive correlation between GWC and oil palm age ($r = 0.277$; p -value = 0.000). The GWC of 9 years old oil palm (263% w/w) is significantly lower than GWC of 12 years old oil palm (362% w/w), indicating closed canopy tend to conserve soil moisture. It is probably related to the higher CO_2 flux at the plot of 9-year-old oil palm ($0.60 \text{ g CO}_2 \text{ m}^{-2} \text{ hr}^{-1}$) compared to CO_2 flux at the plot of 12 years old oil palm ($0.38 \text{ g CO}_2 \text{ m}^{-2} \text{ hr}^{-1}$).

There is negative correlation between CO_2 fluxes and ORP. The correlation is found higher when GWL close to the surface ($\text{GWL} < 50 \text{ cm}$). The ORP have strong negative correlation with soil pH ($r = -0.550$; p -value = 0.000) and high positive correlation (p -value < 0.01) with crop age ($r = 0.349$), groundwater level ($r = 0.319$) and gravimetric water content ($r = 0.146$).

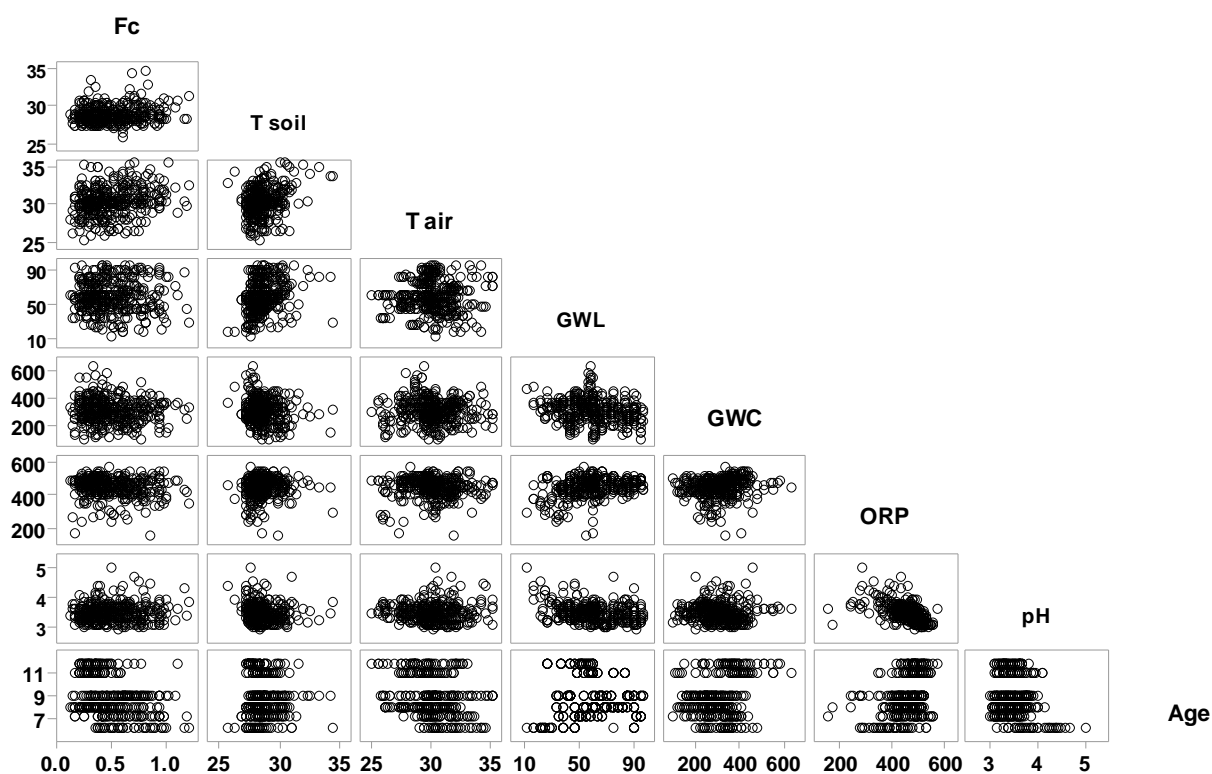


Figure 3. Scatter matrix between CO_2 Fluxes (Fc , $\text{g CO}_2 \text{ m}^{-2} \text{ hour}^{-1}$) and the environmental variables i.e. soil temperature (T soil , $^\circ\text{C}$), air temperature (T air , $^\circ\text{C}$), groundwater level (GWL , cm), gravimetric water content (GWC , %), oxidative reductive potential (ORP , mV), soil pH (pH) and crop age (Age , years after planting)

Table 3. Linear correlation between CO₂ fluxes and environmental characteristics

Environmental characteristics	Pearson correlation; p value		
	GWL ≤ 50 cm; n= 123	GWL > 50 cm; n =241	Total; n = 364
Soil Temperature	0.183; 0.043	0.191; 0.003	0.166; 0.002
Air Temperature	0.117; 0.197	0.270; 0.000	0.221; 0.000
Groundwater Level (GWL)	-0.080; 0.378	0.217; 0.001	-0.01; 0.857
Gravimetric Water Content (GWC)	0.056; 0.535	-0.102; 0.115	-0.046; 0.384
Soil pH	0.145; 0.109	0.012; 0.858	0.089; 0.092
Oxidative Reductive Potential	-0.236; 0.009	0.021; 0.751	-0.116; 0.027
Crop age	-0.507; 0.000	-0.266; 0.000	-0.375; 0.000

Discussion

The CO₂ fluxes measured in this study are within the range of published values of CO₂ flux from oil palm plantation on peatland. In Jambi province, CO₂ emission from oil palm plantation was reported 46.1 ± 30 ton CO₂ ha⁻¹ year⁻¹ (Marwanto and Agus 2014), 34 ± 16 and 45 ± 25 ton CO₂ ha⁻¹ year⁻¹ (Husnain et al. 2014). In Riau province, the CO₂ emission was reported higher at 66 ± 25 ton CO₂ ha⁻¹ year⁻¹ (Husnain et al. 2014). While in Malaysia, CO₂ emission from oil palm plantation was ranging 22.1–117.5 ton CO₂ ha⁻¹ year⁻¹ (Melling et al. 2013; Ishikura et al. 2018; Matysek et al. 2018).

We found that CO₂ fluxes at Site 1 were significantly lower than fluxes at Site 2. It may be related to the difference of chemical characteristics between sites. Ash content at Site 2 ranged from 1.0 to 21.7% and mean ± standard deviation is 5.2 ± 4.9%, were significantly higher from ash content at Site 1. It may influence the higher CO₂ flux in Site 1, as reported by Moilanen et al. (2012) that ash application on peat surface has increased soil pH and CO₂ efflux significantly.

The CO₂ fluxes have significant correlation with soil and air temperature. It is consistent with Berglund et al. (2010) that found significant correlation between CO₂ emission and soil temperature using a lysimeter and incubation method in fen peat of Sweden. The effect of temperature in accelerating CO₂ emission expressed as temperature quotient (Q₁₀) were reported higher when peat soil samples incubated in 22–30°C compared to the samples incubated at 10°C (Kechavarzi et al. 2010). Linear relationship between CO₂ flux and air and soil temperature were also found at 5 years after planting oil palm in Malaysia (r was 0.27 and 0.27 respectively for air and soil temperature) as stated in Melling et al. (2013). Higher temperature may accelerate decomposition rate of soil organic carbon by increasing microbial activities (Liu et al. 2018) and resulting higher CO₂ emission.

Crop ages representing growth stages were significantly correlated with CO₂ fluxes. The effect of crop age relates to the influence in regulating local microclimate through the impact of leaf area index and canopy structure on evaporative demand and vapor pressure deficit (Jucker et al. 2018). Higher and denser canopy result in higher evaporative demand and less energy for sensible heat or air temperature (Sabajo et al. 2017; Bright et al. 2015) leading to lower air and soil temperature (Luskin and Potts 2011). Air beneath canopies with high leaf area index (older oil palm) is cooler and has higher relative humidity during the

day (Hardwick et al. 2015; Melling et al. 2013). The younger oil palm plantation results in the higher soil temperature probably due to the less canopy cover and hence increase the CO₂ fluxes have been reported by some studies (Murdiyarso et al. 2019; Jauhiainen et al. 2014).

Several studies exhibited the effect of oil palm age on CO₂ flux. Matysek et al. (2018) found that the average soil respiration of year 2000 established oil palm plantation was 1.341 gCO₂ m⁻² hr⁻¹ which is higher compared to soil respiration of oil plantation that was established in the year 1978 and replanted in the year 2006 (0.988 gCO₂ m⁻² hr⁻¹) and they argued the decline of soil organic carbon at the second generation of plantation might be responsible for the difference.

Drainage development, that always associated with plantation on peatland, contributes to changes in energy balance for air and soil warming. Draining the excess of water to provide aerobic layer can lower the groundwater table and increase air and soil temperature. The tendency of higher soil temperature at deeper groundwater level was reported by Ishikura et al. (2017) and Wakhid et al. (2018). As a result, microbial activities in peat decomposition process increase and release a significant amount of carbon to the atmosphere. Our study reveals the effect of groundwater level on CO₂ flux is significant when the groundwater table was deeper than 50 cm. The results are in line with other studies that reporting groundwater level effect on CO₂ flux. Carlson et al. (2015) developed model of CO₂ flux based on groundwater level data compiled from 12 studies at 59 sites with the average value of groundwater level was 67 ± 20 cm. Linear relationship of CO₂ flux and groundwater level published by Hooijer et al. (2009) was also derived from groundwater level data between 50 and 100 cm. Further, study of Marwanto et al. (2019) showed that CO₂ fluxes from 50 cm depth of peat subsoil layers under mature oil palm plantation was significantly higher than CO₂ fluxes from the upper depth layers. When groundwater levels were lower than 50 cm, soil temperature dominantly influenced the rate of CO₂ released from peat compared to groundwater levels. It is consistent with the experiment of Sjögersten et al. (2018) reporting the higher impact of temperature on CO₂ emission at the oxygenated flooded condition in the laboratory.

This study reveals soil temperature is the important factor in determining CO₂ flux from oil palm plantation. Crop age, groundwater level and gravimetric water content affected the CO₂ fluxes indirectly through regulating soil

temperature. The CO₂ flux resulted from maintaining groundwater level at a maximum of 40 cm as stipulated in the government regulation may decrease if soil temperature is also maintained from soil warming. Increasing canopy cover, planting the leguminous cover crop or applying mulch from empty fruit bunch are several options to reduce peat surface temperatures and this may, in turn, reduce aerobic peat decomposition rate.

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