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Factors affecting oxidative peat decomposition due to land use in tropical peat swamp forests in Indonesia

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Abstract

The increasing frequency of fire due to drainage of tropical peatland has become a major environmental problem in Southeast Asia. To clarify the effects of changes in land use on carbon dioxide emissions, we measured oxidative peat decomposition (PD) at different stages of disturbance at three sites in Central Kalimantan, Indonesia: an undrained peat swamp forest (UF), a heavily drained peat swamp forest (DF), and a drained and burned ex-forest (DB).

 PD exhibited seasonality, being less in the wet season and greater in the dry season.

From February 2014 to December 2015, mean PD (± SE) were 1.90 ± 0.19, 2.30 ± 0.33, and 1.97 ± 0.25 µmol m^{-2} s^{-1} at UF, DF, and DB, respectively. The groundwater level (GWL) was a major controlling factor of PD at all sites. At UF and DF, PD and GWL showed significant quadratic relationships. At DB, PD and GWL showed significant positive and negative relationships during the dry and wet seasons, respectively. Using these relationships, we estimated annual PD from GWL data for 2014 and 2015 as 698 and 745 g C m^{-2} yr^{-1} at UF (mean GWL: -0.23 and -0.39 m), 775 and 825 g C m^{-2} yr^{-1} at DF (-0.55 and -0.59 m), and 646 and 748 g C m^{-2} yr^{-1} at DB -0.22 and -0.62 m), respectively.   The annual PD was significantly higher in DF than in UF or DB, in both years. Despite the very dry conditions, the annual PD values at these sites were much lower than those reported for tropical peat at plantations (e.g., oil palm, rubber, and acacia). The differences in the relationship between PD and GWL indicate that separate estimations are required for each type of land. Moreover, our results suggest that PD can be enhanced by drainage both in forests and at burned sites.

1. Introduction

Southeast Asia contains an abundance of peat, found as peat swamp forests (Page *et al*., 2004), which are distributed predominantly in Indonesia and Malaysia. Indonesia has the largest area of tropical peat in the world, over 2.48×10^5 km^2, accounting for about 56% of global tropical peatland area; Indonesia's peatland stores up to 68.5 Gt of soil carbon (C), or 77% of soil C in global tropical peatlands (Page *et al*., 2011). However, vulnerable peat swamp forest ecosystems have been devastated by extensive logging and land development involving deforestation and drainage since the 1970s (Sorensen, 1993). As a result, large areas of peat swamp forest have been converted into secondary forests, plantations, and abandoned open shrub and fern lands due to repeated peat fires. For example, the amount of open land has increased from 7% to 15% of total land area over the last two decades (Miettinen *et al*., 2012; 2016). Deforestation can raise soil temperatures (Sano *et al*., 2010), and drainage directly lowers the groundwater level (GWL). Land conversion with deforestation and drainage accelerates oxidative peat decomposition (PD), because of increases in temperature and aeration (Couwenberg *et al*., 2010; Hooijer *et al*., 2012). Extensive forest exploitation following peat drainage for agricultural expansion (e.g., the creation of oil palm and acacia plantations) can lead to catastrophic peat fires (Langner and Siegert, 2009; Yulianti *et al*., 2012). The frequency of fires may explain why the area of abandoned and unused peatland has increased

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threefold from 1.2 to 3.5 Mha since 1990, as landowners have given up on managing their land (Miettinen and Liew, 2010).

Conversion of peatland inevitably leads to aeration and consequent PD, resulting in substantial carbon dioxide (CO_2) emissions into the atmosphere (e.g., Melling *et al.*, 2005; Couwenberg *et al.*, 2010, 2011; Hooijer *et al.*, 2014; Hirano *et al.*, 2014; Könönen *et al.*, 2015). Annual C losses through peat drainage and fires are on average 28 times greater than pre-disturbance rates (Dommain *et al.*, 2014). According to the Wetland Supplement (IPCC, 2014), default CO_2 emissions from tropical peatlands (i.e., emission factors [EFs]) range from 150 to 2000 g C m^{-2} y^{-1}, although this was determined using limited data from fewer than 50 peer-reviewed papers.

The 2006 Intergovernmental Panel on Climate Change Guidelines (IPCC, 2006) generally provides methods for the estimation of greenhouse gases at three levels of detail, from Tier 1 (the default method) to Tier 3 (the most detailed method). The IPCC offers accurate EFs, but deriving EFs from tropical peatlands is a scientific challenge. The Tier 3 approach is not yet feasible due to a lack of accurate data (Couwenberg and Hooijer, 2013); thus, more field data are required from various types of land use in tropical peatlands (Krisnawati *et al.*, 2015). Therefore, this study included sites representing three types of land use, with different levels of disturbance (minimal, moderate, and intensive)

due to drainage and repeated forest fires in an edaphically similar area.

Direct chamber measurements have been made to obtain accurate C loss data from tropical peatland (e.g., Couwenberg *et al*., 2010; Hooijer *et al*., 2010, 2012; Jauhiainen *et al*., 2012; Couwenberg and Hooijer, 2013). However, few studies have reported PD by heterotrophic respiration alone (Jauhiainen *et al*., 2012; Hirano *et al*., 2014), separate from peat total soil respiration (SR), including litter decomposition and root respiration (RR). RR may be responsible for various amounts of total SR, from <10% to 90%, so SR measurements alone are inadequate for determining CO_2 emissions from PD (Couwenbeg *et al*., 2010). Few studies have directly measured PD using the chamber technique; these measurements have been taken for tropical peat in an acacia plantation (Jauhiainen *et al*., 2012), oil palm plantation (Dariah al., 2014; Husnain *et al*., 2014), mixed forest (Melling *et al*., 2013), and drained and burned ex-forest (Hirano *et al*., 2014).

Therefore, we measured PD in three types of tropical peatlands using the closed-chamber method with trenching, to exclude root respiration (RR). Then, to understand how the environmental factors affects CO_2 fluxes, we compared the results from different types of land use under the same geophysical conditions. Wakhid *et al*. (2017) recently reported both PD and SR for compacted peat in a rubber plantation only 25 km from our observation sites, enabling us to compare our results with data from a plantation. Finally,

seasonal variation and annual CO_2 emissions were estimated using empirical models.

2. Materials and methods
2.1. Study site

This study was conducted in tropical peatland at the upper Sebangau River

Catchment, located about 20 km south of the city of Palangka Raya, Central Kalimantan

province, Indonesia (Fig. 1). A large peatland area was deforested and drained in this

province in the late 1990s under the auspices of the national Mega Rice Project. The

project was terminated in 1999, but not before it had resulted in vast areas of degraded

peatland. Our three study sites were located on flat terrain within 15 km of each other and

included a largely undrained peat swamp forest (UF; 2.32°S, 113.90°E), a drained peat

swamp forest (DF; 2.35°S, 114.04°E), and a drained and burned ex-peat swamp forest

(DB; 2.34°S, 114.04°E) that had experienced repeated fires and was characterized by

vegetation regrowth dominated by pioneer species such as ferns (Hirano *et al.*, 2012). DB

had experienced fires at least four times, in 1997, 2002, 2009, and 2014, which were El

Niño years. DF and DB were drained due to the creation of a large canal (width: 25 m,

depth: 3.5–4.5 m) excavated in 1996 and 1997 (Page *et al.*, 2009). In addition, smaller

canals were constructed near DB in May to June 2014 (during our observation period),

with the aim of expanding an oil palm plantation. Notably, in the dry season of October

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2014, a peat fire that approached within a few meters of the study plots occurred at DB.

A strong El Niño event occurred in 2015, and a large forest fire occurred near the study

site. The peat depths at UF, DF, and DB were approximately 3.0, 4.5, and 4.5 m,

respectively. Further information on each site is available in our previous paper (Hirano
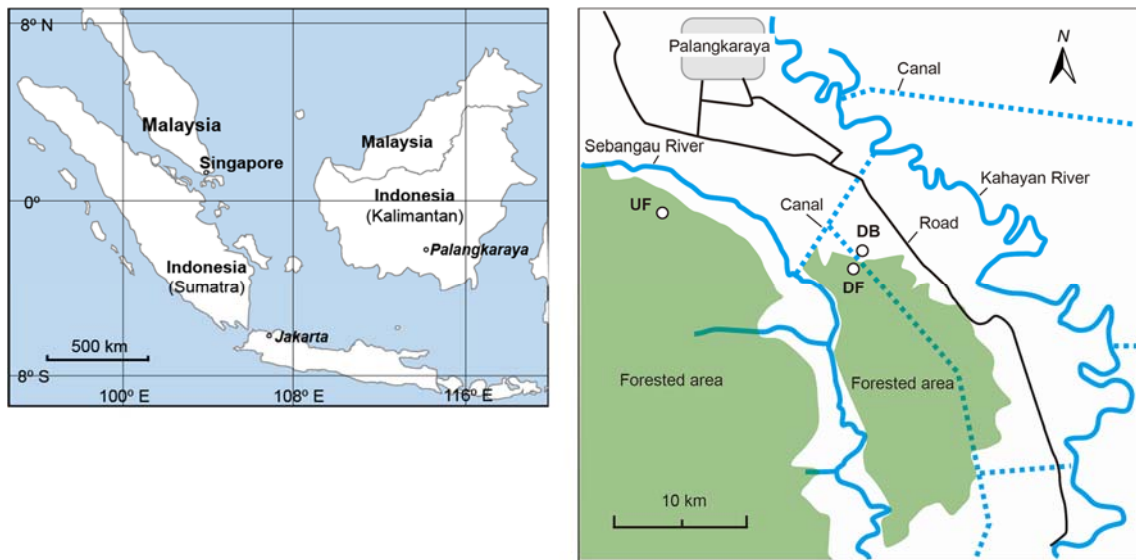
et al., 2012).

Fig. 1. Locations of Palangkaraya in Central Kalimantan, Indonesia and the research sites.

The annual air temperature over 14 years (2002–2015) was 26.2°C ± 0.2°C (mean

± 1 standard deviation [SD]). The annual precipitation for the same period was 2546 ±

466 mm yr^{-1}, measured on a tower at DF (Hirano *et al*., 2012).

2.2. Measurements of groundwater level and soil and air temperatures

The GWL was measured hourly in perforated PVC pipes as the distance of the

groundwater from the surface of the ground using a water pressure sensor (HTV-050KP; Sensez, Tokyo, Japan) from January 2014 to December 2015. The soil temperature was measured hourly at a depth of 5 cm, inside a trench, using a temperature logger (Thermochron SL-type; KN Laboratories Inc., Osaka, Japan) in each plot.

2.3. Peat properties

Peat soil was sampled in September 2014, when the GWL was at its lowest point during the year. At each site, a pit was dug approximately 80 cm deep at least 1 m from any trees. Five replicates of core samples (volume: 100 cm^3) were collected using sharpened steel cylinders to avoid peat compression. Samples were divided by depth into peat layers of 0–5, 10–15, 20–25, 30–35, 50–55, and 70–75 cm for UF (apart from the layers 50–55 and 70–75 cm), DF (all), and DB (apart from 70–75 cm) in accordance with the GWL. A total of 90 peat samples were collected and oven-dried at 105°C for up to 96 h. The C and nitrogen (N) contents of the peat soil were determined with a CN analyzer (Sumigraph NCH-22; Sumika Chemical Analysis Service Ltd., Osaka, Japan).

2.4. Soil carbon dioxide efflux measurements

Three trenches were installed within 50 m from a flux tower at each site in September 2013. Square trenched plots (1 m × 1 m) were established by making 1 m deep cuts into

the ground along the boundaries with a steel knife and using a shovel to sever all roots. For each plot, four 2 mm thick polyethylene boards (1.2 m × 1 m) were inserted vertically into the soil to prevent root invasion. All plants were removed from the peat inside the trench before chamber installation. Any fern and sedge plants that had regrown inside the collars and trenches were removed periodically. In addition, leaf litter was removed from the collars before measurement. These precautions ensured that the CO_2 efflux of the soil was equivalent to PD, and RR could be completely eliminated. In each trench, 4 PVC collars (diameter: 21 cm, height: 2 cm) were placed 3 cm deep, for a total of 12 collars at each site. The collars had grooves on their tops that allowed them to be filled with water.

The CO_2 efflux from the peat surface was measured following the closed-chamber method. A portable infrared gas analyzer (GMP343; Vaisala, Helsinki, Finland) was attached to an opaque PVC chamber. The ground-covering area and volume of the chamber headspace were 0.0491 m^2 and 0.0074 m^3, respectively. The effective volume of the chamber was calculated in accordance with the varying heights of the collar due to soil subsidence and applied to the calculation of CO_2 efflux. To shorten response times, the dust filter was detached from the portable infrared gas analyzer. No fans were used to mix the air in the chamber, but the air in the chamber headspace was replaced with ambient air using a fan before each measurement.

Soil CO_2 effluxes from microbial PD were measured three times a day, at 10:00, 11:30, and 14:00, midway through each month. After trench installation in September 2013, we waited until the start of February 2014 to begin measurements to minimize the effects of the decomposition of recently killed roots, which could contribute to overestimations of PD (Sulzman *et al*., 2005). During the measurements, the chamber was placed securely over the chamber collar. The chamber was kept airtight by filling the collar groove with water. CO_2 concentrations were measured every 5 s over 3 min and recorded using a data logger (LR5042; Hioki, Nagano, Japan). The rate of increase of the CO_2 was calculated with linear fitting using the least-squares method. The CO_2 analyzer was calibrated every three months using standard gases at two CO_2 concentrations. The monthly measurements began in February 2014 and lasted until December 2015. If measurements could not be performed due to heavy rain, we took the results of another sample or the average of two samples on the sampling date. In addition, we could not conduct measurements in October 2014 for sites DF and DB and in October 2015 for all sites because of an expanding peat fire and an analyzer malfunction, respectively. During the waterlogged period, we doubled the chamber collar to increase the measurement height. Air temperatures in the chamber headspace were measured every 5 s using a temperature logger (LR5011, Hioki), and soil temperatures were measured at a depth of

5 cm using a digital thermometer at each plot. The efflux of soil CO_2 (μmol mol^{-1} m^{-2} s^{-1}) was calculated using the air temperature and the increasing rate of CO_2 concentration (dC/dt, μmol s^{-1}) using Eq. (1):

$$CO_2\ efflux = (dC/dt) * (V/V'(273.2 + T_a)/273.2))/A \qquad (1)$$

where V is the effective chamber volume (m^3), V' is the molar volume of air at 0°C (0.0224 m^3 mol^{-1}), and A is the ground area covered by the chamber (m^2). A linearity test was applied to assess the quality of dC/dt, following the approach of Aguilos $et\ al$. (2013).

Statistical tests were performed using R ver. 3.3.1 (R Development Core Team, 2016). Differences among the treatment groups were analyzed using analysis of variance, and specific differences among groups were analyzed using Tukey's multiple comparison test.

3. Results
3.1. Seasonal variation in environmental factors

The levels of annual precipitation in 2014 and 2015 were 2199 and 2380 mm yr^{-1}, respectively, 13.6% and 6.5% lower than the 14-year average from 2002 to 2015 (Fig. 2a). The dry season lasted for 3–4 months, from June or July, based on the commonly used criterion of monthly precipitation less than 100 mm (e.g., Malhi and Wright, 2004). These long dry seasons, particularly that of 2015, were probably caused by strong El Niño events (Schiermeier, 2015).

GWL began to decrease at the beginning of the dry period (mid-July in 2014 and early August in 2015) and remained low until the end of the dry period (mid-November in 2014 and late October in 2015). The dry season of 2014 was longer than that of 2015, although maximum drawdown of the GWLs at all sites was greater in 2015 than 2014 (Fig. 2a, 2c). GWLs began to increase with the onset of the rainy season and peaked in late April in 2014 and mid-March in 2015. The lowest GWLs at UF, DF, and DB in 2015 were -1.43, -1.62, and -1.52 m, respectively (Fig. 2c). Mean annual GWLs in both observation years were much lower than the 11-year mean GWLs (2005–2015) at all sites: DF, -0.55 m (2014), -0.59 m (2015), and -0.47 m (11-year mean); UF, -0.23 m (2014), -0.39 m (2015; lowest in 11 years), and -0.15 m (11-year mean); and DB, -0.22 m (2014), -0.63 m (2015; lowest in 11 years), and -0.14 m (11-year mean). Comparing the 2 observation years, mean GWLs were lower in 2015 than in 2014 at all three sites, due to the prolonged dry season caused by a strong El Niño event in 2015. Furthermore, the much lower GWL in 2015 at DB was exacerbated by a newly constructed drainage canal for an oil palm plantation near DB around June 2014. The GWL was lower at DF than at DB in 2014, but they were almost the same in 2015, probably due to the effects of the new canal. The GWL at DF was lower than the levels at UF and DB ($p < 10^{-7}$) in 2014, but a significant difference was only observed between the levels at DF and UF in 2015.

The daily mean soil temperatures at a depth of 5 cm were 26.2°C, 26.1°C, and

28.7°C at UF, DF, and DB, respectively. The highest soil temperature was recorded at DB,

reaching a maximum of 31.2°C. The soil temperature at DB was significantly higher than

temperatures at the other two sites ($p < 10^{-10}$), because DB was more exposed to solar

radiation during the day due to its sparser vegetation cover. Soil temperatures at DF and

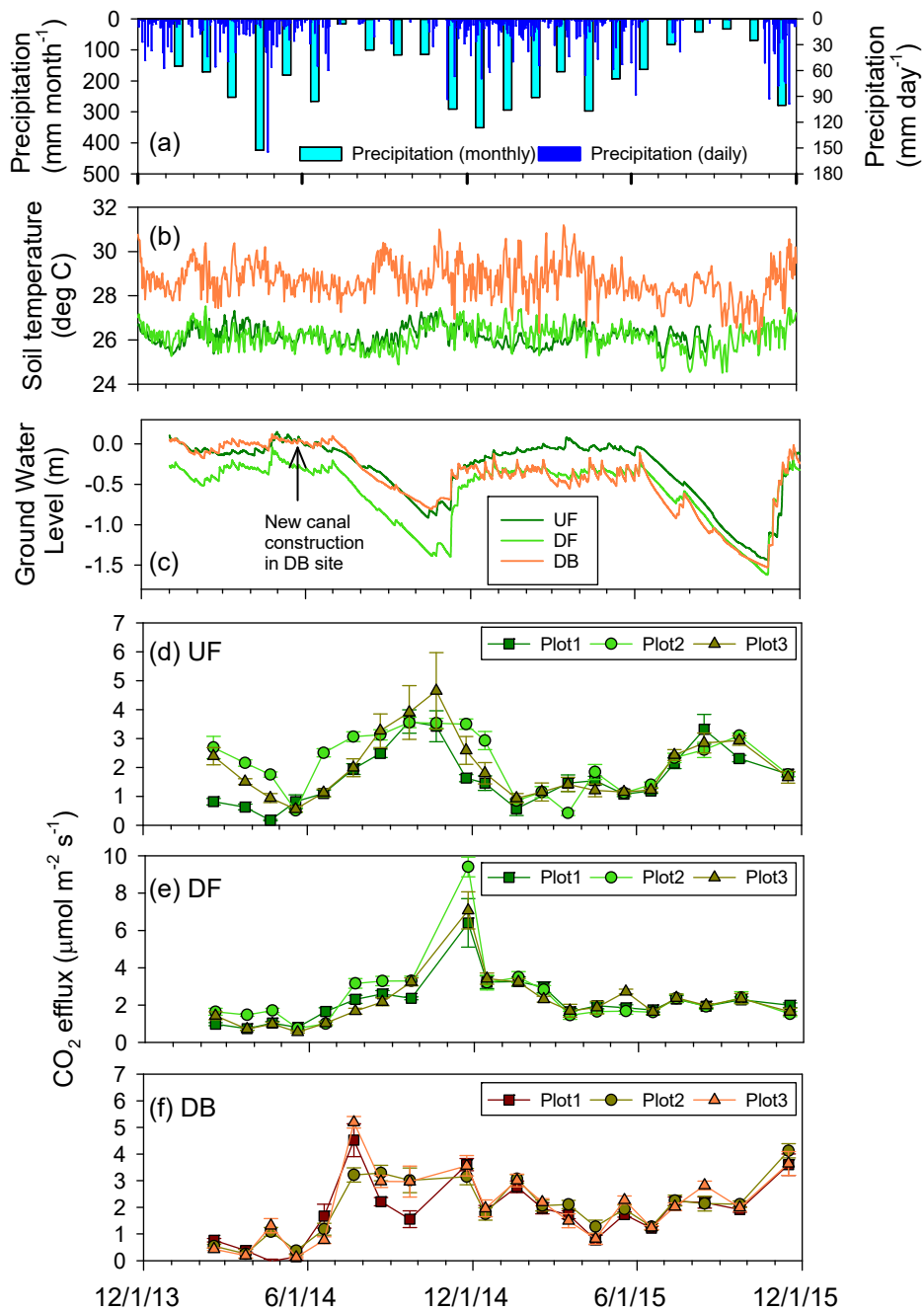UF were similar ($p > 0.05$), and never exceeded 30°C (Fig. 2b).

Fig. 2. Seasonal variation in (a) daily and monthly precipitation at drained and burned forest [DB], (b) daily mean soil temperature at a depth of 5 cm, (c) daily mean groundwater level, and (d), (e), (f), CO_2 efflux at each sampling plot (mean ± SE) at the study sites, undrained forest [UF], drained forest [DF], and DB, respectively.

3.2. Carbon and nitrogen content and bulk density of peat

There was no obvious difference in bulk density among sampling depths at UF and DF (Table 2). By contrast, bulk density in the surface layer (0–5 cm) was significantly higher than in the deeper layers at DB ($p < 10^{-8}$; Table 1). The bulk density in the surface layer at DB was almost two times higher than those at UF and DF. The C content gradually increased with depth at UF, whereas it remained almost the same at all depths at the other sites, apart from the 30–35 cm layer at DF (Table 1). The C content in the 0–5 cm layer was significantly higher at DB ($p < 10^{-3}$; Table 1). The N content gradually decreased with depth at all sites. In deeper layers, the N content was much lower at DF and DB than at UF. The N content at UF remained above 1.4% until a depth of 45 cm, which was similar to the results of Lampera *et al.* (2014). By contrast, it fell below 1% at depths of 30 cm and 10 cm at DF and DB, respectively. The three sites had different C/N ratio profiles: the UF site had the lowest ratios, followed by DF and then DB. The C/N ratio at DB was much higher than those of the other two sites; it was 41.9 in the surface layer and exceeded 60 in layers below a depth of 10 cm (Table 1).

Table 1. Main characteristics of the peat at the study sites (mean ± SD, $n = 5$).

Site	Sampling depth (cm)	Bulk density (g cm^{-3})	C content (%)	N content (%)	C/N
UF	0–5	0.11 ± 0.01	49.9 ± 0.2	1.90 ± 0.07	26.3 ± 0.8
	10–15	0.11 ± 0.00	50.3 ± 0.5	1.82 ± 0.08	27.7 ± 2.2
	15–20	0.09 ± 0.00	51.5 ± 0.5	1.76 ± 0.10	29.3 ± 2.0
	20–25	0.09 ± 0.01	51.7 ± 1.2	1.62 ± 0.19	32.3 ± 3.8
	30–35	0.10 ± 0.01	52.6 ± 0.9	1.41 ± 0.16	37.6 ± 4.6
	40–45	0.10 ± 0.01	54.0 ± 1.5	1.42 ± 0.03	38.1 ± 0.6
DF	0–5	0.14 ± 0.01	50.3 ± 0.3	1.60 ± 0.07	31.5 ± 1.3
	10–15	0.13 ± 0.01	54.6 ± 1.4	1.63 ± 0.05	33.5 ± 1.9
	20–25	0.10 ± 0.01	55.0 ± 0.5	1.37 ± 0.03	40.1 ± 1.2
	30–35	0.16 ± 0.01	63.5 ± 1.1	0.91 ± 0.10	70.7 ± 7.6
	50–55	0.14 ± 0.01	53.0 ± 3.5	0.77 ± 0.09	69.5 ± 4.9
	70–75	0.12 ± 0.01	54.8 ± 1.5	0.95 ± 0.31	62.7± 18.3
DB	0–5	0.24 ± 0.02	54.4 ± 1.8	1.30 ± 0.10	41.9 ± 2.0
	10–15	0.14 ± 0.01	53.5 ± 1.8	0.85 ± 0.06	63.0 ± 4.1
	20–25	0.14 ± 0.01	51.8 ± 2.1	0.82 ± 0.05	63.2 ± 3.9
	30–35	0.14 ± 0.01	55.1 ± 4.0	0.78 ± 0.07	70.8 ± 7.3
	50–55	0.11 ± 0.00	53.4 ± 2.7	0.74 ± 0.07	72.8 ± 4.3

3.3. Seasonal variation in oxidative peat decomposition

Because there were no significant differences in PD among the three daily sampling times at each sampling plot throughout the sampling period ($p > 0.05$), the daily average PD value for each sampling plot was used for further analysis. Figure 2d–f shows the seasonal variation in mean CO_2 efflux in the three plots at UF, DF, and DB (mean of the maximum measurements for 12 chambers, which means 4 chambers, three times for each observation date), respectively, from February 2014 to December 2015. PD exhibited

seasonality and was lower in the wet (high-GWL) season and higher in the dry (low-GWL) season. A much larger CO_2 efflux (7.63 ± 0.90 µmol m^{-2} s^{-1}) was observed on 24 November 2014 at DF, which occurred immediately after rainfall during the dry period.

The mean PD values (mean ± standard error) for the entire sampling period were 1.66 ± 0.21, 2.18 ± 0.22, and 1.88 ± 0.19 µmol m^{-2} s^{-1}, at plots 1, 2, and 3, respectively, at UF.

At DF and DB, the mean PD values were 2.20 ± 0.27, 2.49 ± 0.41, and 2.21 ± 0.31 µmol m^{-2} s^{-1} and 1.84 ± 0.26, 2.01 ± 0.24, and 2.05 ± 0.29 µmol m^{-2} s^{-1} at plots 1, 2, and 3, respectively. Excluding the large CO_2 efflux in November 2014 at DF, the mean PD values were 1.98 ± 0.17, 2.13 ± 0.19, and 1.95 ± 0.19 µmol m^{-2} s^{-1} at plots 1, 2, and 3, respectively. These values are much lower than those at a rubber plantation developed after peat compaction (5.96 ± 0.43 µmol m^{-2} s^{-1} with a mean bulk density of 0.23 g cm^{-3} from the surface to 70 cm depth) in the same region (Wakhid *et al.*, 2016). There were no significant differences in annual mean PD between the sampling years (2014 and 2015) at all sites ($p > 0.05$), apart from UF Plot 2 (2015 > 2014, $p = 0.02$). PD at DB was significantly larger ($p < 0.013$) after canal excavation at all sampling plots in the wet season (December–June).

3.4. Relationship of PD with GWL and prediction of PD

The relationship between PD and GWL showed a significant quadratic correlation in

all sampling plots at both UF and DF (Fig. 3a and b). A large CO_2 efflux in November

2014 at DF was removed from the correlation analysis, because rewetting can temporarily

enhance decomposition or respiration during a dry period (as detailed in Ishikura *et al.*,

2017). At DB, PD peaked at the beginning of the dry period and decreased with decreasing

GWL until GWL reached a depth of -1.4 m. By contrast, PD increased with decreasing

GWL in the wet season, when there was a relatively high GWL (Fig. 3d). In both periods,

PD was linearly correlated with GWL at all sampling plots. There were significant but

weak positive relationships between PD and soil temperature at one of the three plots at

UF and all three plots at DB during the dry period ($p < 0.05$). No significant correlation

was observed between PD and soil temperature in all plots at DF ($p > 0.05$).

These results suggest that GWL acted as a major controlling factor for seasonal

variation in PD. This is consistent with many reports from tropical peatlands, including

Sundari *et al.* (2012) and Hirano *et al.* (2014), with data from the same study sites. Thus,

we predicted PD from GWL using the following correlation equation for UF and DF:

$$PD = a * GWL^2 + b * GWL + c \tag{2}$$

and separately for DB for the dry and wet seasons:

$$PD = a * GWL + c \tag{3}$$

where PD is the prediction of the daily average oxidative PD (μmol CO_2 m^{-2} s^{-1}), GWL

is the daily average groundwater level from the ground surface (m), and a, b, and c are coefficients. For DF, the predicted PD was lower than measurements when the GWL exceeded –0.5 m (Fig. 3b), leading to underestimation of the annual PD. Because the larger PD was observed just after the long dry season in 2014, we assumed that continuous dry conditions had some effects on PD, even in the following wet season. Therefore, we also tried to predict PD from the 1-, 2-, 3-, and 4-month mean GWL before each sampling date. This revealed that the 3-month mean antecedent GWL best-explained PD, having the highest coefficient of determination (r^2; Fig. 3c). For DB, we used different a and c values for the dry and wet seasons, with reference to the periods during which GWL decreased and increased. The results of the regression analyses revealed significant correlations between predicted PD and observed PD at all sites and plots (UF: Plots 1, 2, and 3; $F_{1,53} = 151.7$, $p < 10^{-16}$, $F_{1,55} = 49.6$, $p < 10^{-8}$, $F_{1,54} = 124.7$, $p < 10^{-14}$; DF: Plot 1, 2, and 3; $F_{1,54} = 7.6$, $p = 0.008$, $F_{1,54} = 16.8$, $p = 0.0001$, $F_{1,54} = 11.4$, $p = 0.001$; DF (3-month mean GWL) : Plot 1, 2, and 3; $F_{1,54} = 25.0$, $p < 10^{-5}$, $F_{1,54} = 31.0$, $p < 10^{-6}$, $F_{1,54} = 45.4$, $p < 10^{-7}$; DB: Plot 1, 2, and 3; $F_{1,49} = 115.8$, $p < 10^{-13}$, $F_{1,49} = 108.9$, $p < 10^{-13}$, $F_{1,48} = 130.5$, $p < 10^{-14}$) (Fig. 4). Table 2 lists the fit parameters in Eqs. (2) and (3) for each sampling plot.
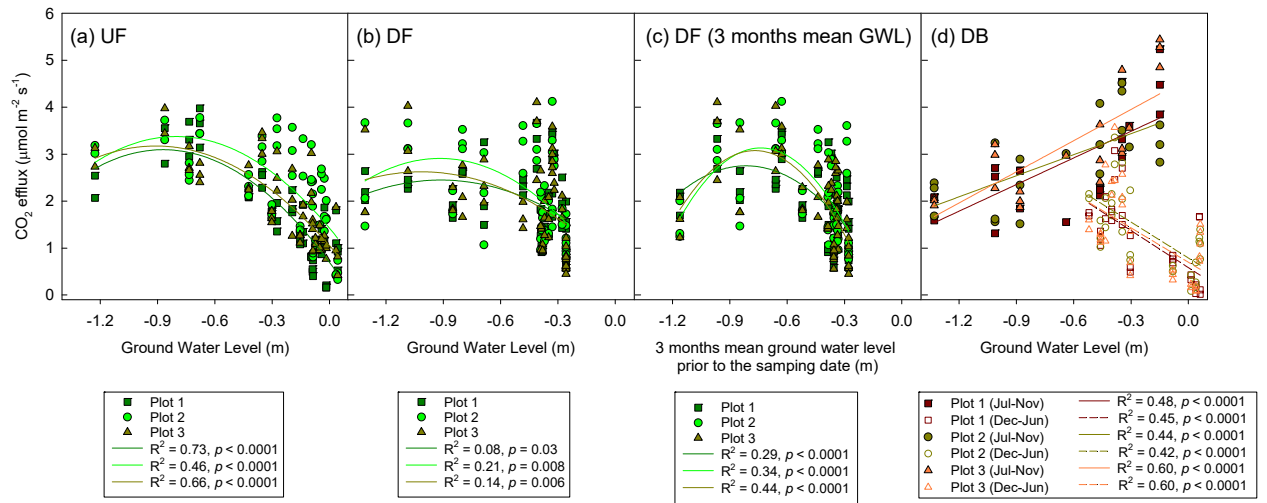
Fig. 3. Relationship between CO_2 efflux (PD) and GWL at (a) UF, (b) DF, (c) DF with 3-month mean GWL before each sampling date, and (d) DB. Quadratic curves were fitted for UF and DF. Linear regression was applied separately for the dry (July–November) and wet (December–June) seasons at DB.
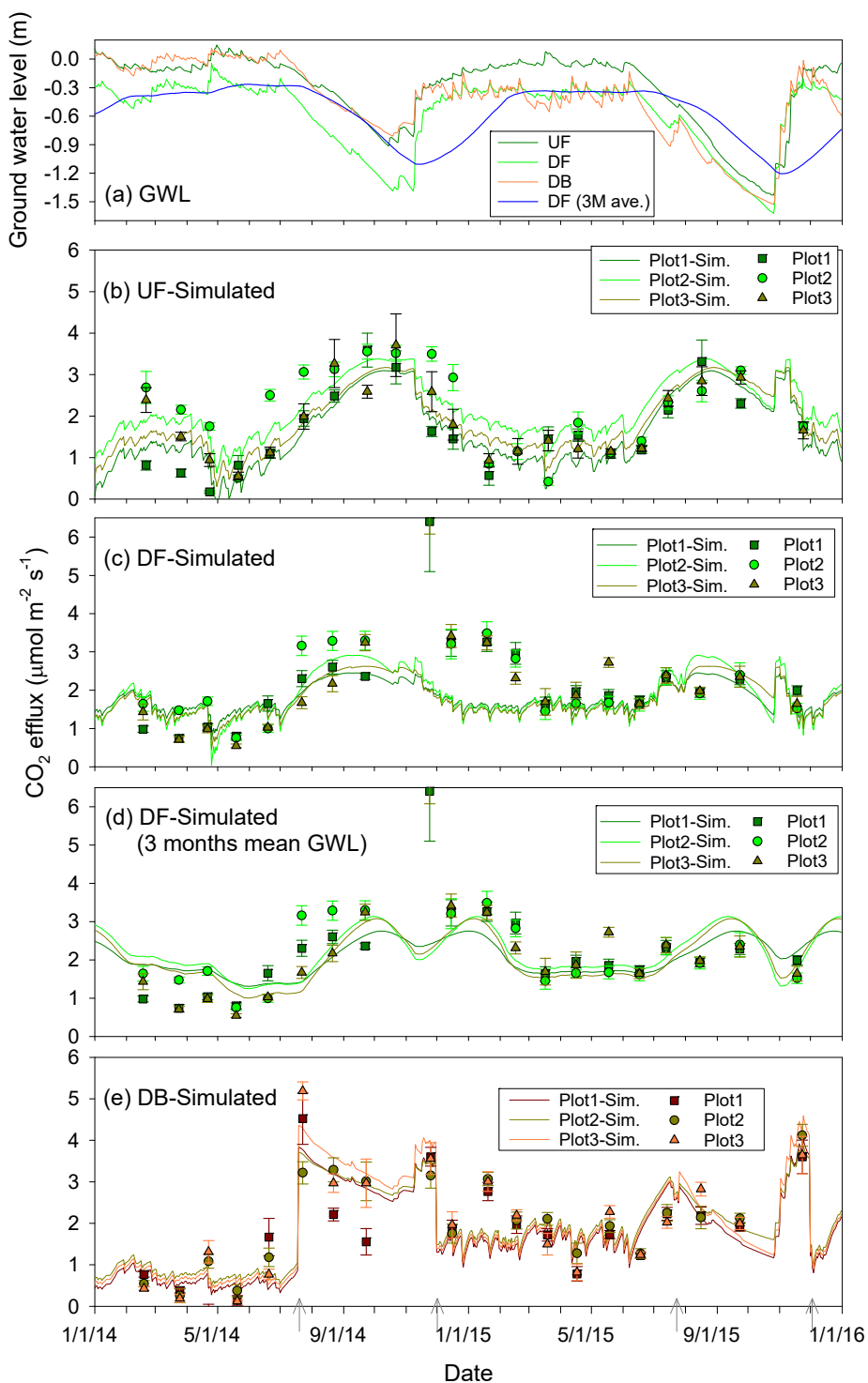
Fig. 4 Results of the prediction of CO_2 efflux from oxidative peat decomposition (b–e) with seasonal variation in the daily mean groundwater level (b, c, e) and 3 month mean groundwater level before the predicted date (d). The measured values are shown as symbols (mean ± SE). The arrows in (e) indicate the change between the dry and wet season.

Table 2. Fit parameters used in Eqs. (2) and (3).
* indicates parameters used in Eq. (2) using the 3-month mean antecedent groundwater level.

	a	b	c
UF (Plot 1)	-3.17	-5.51	0.69
(Plot 2)	-3.04	-4.87	1.43
(Plot 3)	-2.57	-4.67	1.05
DF (Plot 1)	-1.93	-3.52	0.84
(Plot 2)	-3.13	-5.74	0.27
(Plot 3)	-1.95	-3.97	0.61
DF (Plot 1)*	-4.76	-7.76	-0.41
(Plot 2)*	-8.37	-12.4	-1.44
(Plot 3)*	-8.16	-12.5	-1.74
DB (Plot 1: Dry)	1.88	-	4.05
(Plot 2: Dry)	1.49	-	3.88
(Plot 3: Dry)	2.21	-	4.62
DB (Plot 1: Wet)	-2.64	-	0.58
(Plot 2: Wet)	-2.54	-	0.79
(Plot 3: Wet)	-2.45	-	0.69

3.5. Estimation of annual CO_2 emissions from oxidative peat decomposition

CO_2 emissions were estimated from the predicted PD values derived from Eq. (2) for

UF and DF and from Eq. (3) for DB using the daily mean GWL; the estimations were

summed as annual emissions. Table 3 shows the annual estimates of PD for the three

sampling plots and the average PD at the three sites for the 2 observation years. For DF,

PD was estimated from the 3-month mean GWL before the sampling date. The results

revealed a significantly higher mean PD in 2015 than in 2014 at UF Plot 1 ($p = 0.02$) and

UF Plot 3 ($p = 0.006$) , DF Plot 1 ($p = 0.0003$), DF Plot 2 ($p = 0.003$), DF Plot 3 ($p =$

0.0008), and DB Plot 1 ($p < 10^{-4}$), DB Plot 2 ($p < 10^{-6}$), and DB Plot 3 ($p = 0.01$).

Table 3. Annual mean and sum of CO_2 efflux from oxidative peat decomposition predicted from groundwater level in 2014 and 2015. 3-month mean antecedent GWL was used for prediction for DF.

Site and plot	Mean and lowest GWL (m)		Mean CO_2 efflux ($\mu mol\ m^{-2}\ s^{-1}$)		Annual CO_2 emissions (g C m^{-2} y^{-1})	
	2014	2015	2014	2015	2014	2015
UF mean			1.84 ± 0.30	1.97 ± 0.27	698 ± 114	745 ± 99
Plot 1	-0.23,	-0.39,	1.56 ± 0.87	1.71 ± 0.83	591	648
Plot 2	-0.91	-1.43	2.16 ± 0.73	2.23 ± 0.64	818	847
Plot 3			1.80 ± 0.76	1.96 ± 0.75	683	740
DF mean			2.05 ± 0.08	2.18 ± 0.07	775 ± 29	825 ± 26
Plot 1	-0.55,	-0.59,	2.01 ± 0.49	2.13 ± 0.42	760	806
Plot 2	-1.39	-1.62	2.14 ± 0.57	2.26 ± 0.54	808	854
Plot 3			2.00 ± 0.65	2.15 ± 0.58	756	814
DB mean			1.70 ± 0.11	1.98 ± 0.10	646 ± 41	748 ± 37
Plot 1	-0.22,	-0.62,	1.59 ± 1.20	1.87 ± 0.63	601	707
Plot 2	-0.81	-1.53	1.73 ± 1.11	2.05 ± 0.57	655	779
Plot 3			1.80 ± 1.34	2.01 ± 0.73	683	759

4. Discussion
4.1. Factors affecting oxidative peat decomposition

Higher soil temperatures have been reported to enhance SR in tropical peatland (e.g., Melling *et al*., 2005; Ali *et al*., 2006; Ishikura *et al*., 2017); however, our results showed only a weak positive correlation between PD and soil temperature ($p < 0.05$) at DB, which lacked a canopy. Moreover, our results suggest that PD could predominantly be explained

by variation in GWL. There was less precipitation than the average in the 2 observation years, resulting in a lower GWL in the dry season than usual. The relationships between PD and GWL and their regression parameters differed among the study sites (Fig. 3). The r^2 was greater at UF (Fig. 3a) than DF (Figs. 3b and 3c). PD at UF increased with decreasing GWL and peaked at a GWL between -0.6 and -0.9 m. A similar pattern was reported by Sundari *et al*. (2012), who found an increase in total SR with decreasing GWL in many chambers at their UF site. Peat at our undisturbed UF site, with a lower bulk density and greater porosity (Table 1), probably contributed to high water permeability and gas transport (oxygen and CO_2) under low-GWL conditions, resulting in the greater correlation between PD and GWL. The greater PD at Plot 2 than the other two plots at UF, even during high-GWL conditions, could be explained by its higher elevation (Fig. 3a) than that of the other two plots.

In contrast, r^2 values at DF with GWL on the sampling date were much lower (Fig. 3b). During the 2 observation years (2014 and 2015), the GWL remained below the peat surface even during the wet season at DF. PD in the peat layer above the GWL remained high even during the high-GWL period, resulting in an unclear relationship between PD and daily GWL. In addition, there were large discrepancies between the measurements and predictions during the post-dry period in 2014 (Fig. 4c), implying that other factors besides GWL enhanced PD after the dry period in 2014. Ishikura *et al*. (2017) examined the larger SR rate during the rewetting period in cropland on tropical peatland. They

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considered that the decomposition of labile organic matter derived from dead microbes and that the modification of organic matter during dry periods (Birch 1958; Marumoto *et al*., 1977; van Gestel *et al*., 1993) contributed to the enhanced CO_2 emissions. Under non-waterlogged conditions, even in the early rainy season, the enhancement of PD by rewetting of surface peat likely contributed to greater CO_2 emissions (Figs. 2c and 2e). Using the 3-month mean antecedent GWL, a high PD during the post-dry period was predicted (i.e., with higher r^2 values; Figs. 3c and 4d). This recorded effect of dryness implies that PD in the surface layer remained at a higher level after the longer dry period than in a normal year (especially in 2014). This explanation was supported by the results of Kwon *et al*. (2013), who conducted peat incubation experiments under dry conditions, and suggests that more CO_2 was emitted due to peat oxidation from drained tropical peat than from pristine peat for the same GWL, because oxidative enzymic activities were enhanced by drainage. Therefore, PD was larger in DF than UF in both 2014 and 2015 ($p < 0.001$). This phenomenon seems to be typical of a site where the peat surface seldom experiences waterlogged conditions and is oxidized consequently, even during the wet period. However, more intensive observation is needed to confirm this hypothesis.

The predicted PD in DB was significantly smaller than in DF in both 2014 and 2015 ($p < 0.01$). The range in the observed PD at DB did not differ significantly from the other two sites, although the soil temperature at DB was significantly higher. Considering that higher soil temperatures enhances decomposition, this implies that potential decomposition was lower at DB, which can probably be attributed to its less-aerobic conditions, higher bulk density, and lower nutrient conditions (i.e., high C/N), particularly

in surface peat, than in the other two sites (Table 1). The result is consistent with a study by Könönen *et al*. (2016) conducted in the same area. That study found that surface peat in an open burnt site contained fewer labile compounds (hemicelluloses, extractives, uronic acids, and cellulose) and more recalcitrant acid insoluble lignin than a forest site.

The seasonal pattern in PD at DB differed from the other sites, with a peak early in the dry period, when the GWL began to lower, particularly in 2014 (Fig. 2f). There were differences in the physical and chemical characteristics between the pre- (UF and DF) and post-burned (DB) sites. This difference was attributable to the decreased water and gaseous permeability due to the higher bulk density of the surface layer (Table 2) after peat fires. Surface peat, with its low porosity, can function as a gas transport barrier between the atmosphere and deeper peat layers, particularly during periods with higher GWLs, because the pores are filled with water. Decreases in the GWL after the waterlogged conditions of July 2014 probably ended the barrier effect, accelerating surface PD. In the same period in 2015, we did not observe a PD peak. The lower GWL due to the newly excavated drainage canal probably contributed to maintaining greater PD ($p < 0.013$) even during the wet season (December 2014 to June 2015) than in the previous year. However, PD decreased with decreasing GWL below around -0.5 m (Fig. 3d). This phenomenon may be explained by the characteristics of the peat at DB, given

that a lower gas permeability would prevent oxygen transport to deeper peat layers and that some of the readily decomposable fresh litter had been burned (Christian *et al*., 2003). This latter explanation is supported by the much lower N content and higher C/N ratio at DB than at the other two sites (Table 1). Soil organic matter with C/N ratios greater than 20 typically requires additional N to support decomposition (Snyder *et al*. 2009). As a result, an enhancement in microbial PD in deeper peat layers cannot be expected even during the dry period in burned peat sites. These factors may explain the different response of PD to variation in GWL at DB from the response in the other sites (Figs. 3d and 4e).

Wakhid *et al*. (2017) showed a clear relationship between GWL and PD in a nearby rubber plantation established using heavy machinery after peat compaction; their study site was located 25 km from ours. In their results, the CO_2 efflux from PD increased linearly with decreasing GWL ($r^2 = 0.94$–0.98). Our results showed different relationships with GWL than theirs did, probably because of the higher bulk density (around 0.23 g cm^{-3} from 0–75 cm depth) at the plantation site and more vertically homogenized peat conditions, due to peat compaction. By contrast, at our sites, the peat was more porous and the topographic conditions were more heterogeneous, with hollows and hummocks, at UF and DF, while DB had a relatively uneven surface due to the burned peat. The small-

scale hydrology at our non-plantation sites likely affected PD (e.g., Hirano *et al*., 2009;

Page *et al*., 2009; Sundari *et al*., 2012; Jauhiainen *et al*., 2012, 2014; Hirano *et al*., 2014).

This comparison suggests that PD can be predicted more easily at plantations than at non-

compacted natural peat sites.

Table 4. Comparison of annual carbon dioxide emissions from oxidative peat decomposition with previous studies using the chamber method (revised from Wakhid *et al.*, 2017).

Type of land use	CO_2 emission (g C m^{-2} y^{-1})	Mean GWL (m)	Bulk density (g cm^{-3})	C** (%)	N** (%)	Fertilizer ***	Treatment ****	Reference	Note†
Oil palm plantation	1042	-0.52	0.16	45	1.5	Y	I	Dariah *et al.*, 2014	Jambi, ID (6 years)
Oil palm plantation	930	-1.14	0.19	49	2.1	Y	I	Dariah *et al.*, 2014	Jambi, ID (15 years)
Oil palm plantation	1800	-0.72	NA	NA	NA	Y	I	Husnain *et al.*, 2014	Riau, ID
Oil palm plantation	693	-0.58	0.20	46	1.8	Y	T	Melling *et al.*, 2013	Sarawak, MY
Acacia plantation	2182	-0.80	0.09	NA	NA	NA	T & I	Jauhiainen *et al.*, 2012	Riau, ID
Sago plantation	762	-0.24	0.15	45	2.0	N	T	Melling *et al.*, 2013	Sarawak, MY
Rubber plantation	1418	-0.67	NA	NA	NA	Y	I	Husnain *et al.*, 2014	Riau, ID
Rubber plantation	1408	-0.69	0.23	43	2.3	Y	T	Wakhid *et al.*, 2017	Cent. Kalimantan, ID
Bare ground	1718	-0.70	0.12	50	1.2	Y	I	Husnain *et al.*, 2014	Riau, ID
Mixed forest	993	-0.46	0.15	48	1.8	N	T	Melling *et al.*, 2013	Sarawak, MY
Burnt & drained forest	450	-0.26	NA	58	NA	N	S	Hooijer *et al.*, 2014	Cent. Kalimantan, ID
Burned forest (DB) ††	382, 362	-0.18, -0.09	NA	NA	NA	N	B	Hirano *et al.*, 2014	Cent. Kalimantan, ID
Undrained forest (UF)	698, 745*	-0.23, -0.39*	0.11	50	1.9	N	T	This study	Cent. Kalimantan, ID
Drained forest (DF)	775, 825*	-0.55, -0.59*	0.14	50	1.6	N	T	This study	Cent. Kalimantan, ID
Burned forest (DB)	646, 748*	-0.22, -0.62*	0.24	54	1.3	N	T	This study	Cent. Kalimantan, ID

* Values are from 2014 and 2015. ** Data from the literature and our observations for the surface layer.

*** Y: Applied, N: Not applied, NA, No data

**** I, T, B, and S indicate inter-rows, trenching, burnt, and subsidence measurements, respectively.

† ID and MY indicate Indonesia and Malaysia, respectively.

†† Values are from 2004–2005 and 2005–2006. Bulk density, C, and N content data are from this study.

NA, not available.

4.2. Comparison to previous research
4.2.1 Studies in the same research area

Sundari et al. (2012) showed the relationships between GWL and total SR at UF and DF using automated chamber data measured in 2004–2005. They estimated the annual SR in 2005 as 1321 and 1244 g C m^{-2} y^{-1}, respectively, for UF and DF, with GWL data using a linear or quadratic equation. The mean GWLs were -0.09 and -0.51 m at UF and DF, respectively. We estimated the annual SR on a daily basis using their equation and determined values of 1662 and 1864 g C m^{-2} y^{-1} at UF (GWL: -0.23 and -0.39 m) and 1296 and 1306 g C m^{-2} y^{-1} at DF (GWL: -0.55 and -0.59 m), in 2014 and 2015, respectively. The drier-than-normal conditions in 2014 and 2015 likely resulted in higher SR estimations. We estimated the PD/SR ratio in 2014 and 2015 at 0.40 ± 0.07 (mean of three plots ± SD) and 0.39 ± 0.06 at UF and 0.59 ± 0.02 and 0.61 ± 0.02 at DF (prediction using 3-month mean antecedent GWL), in 2014 and 2015, respectively. These ratios were roughly equivalent to (UF) or higher (DF) than those reported by Melling et al. (2013), who determined (SR-RR)/SR values of 0.40, 0.38, and 0.48 for a mixed peat swamp forest, oil palm plantation, and sago plantation, respectively. The estimated PD/SR ratio showed seasonal variation and was higher in the dry season than in the wet season, in both UF (mean for July to November; 0.51 ± 0.05 and 0.47 ± 0.03 in 2014 and 2015, respectively) and DF (mean for July to November; 0.67 ± 0.02 and 0.67 ± 0.01 in 2014 and 2015,

respectively). This seasonality suggests that the extensive dry conditions that occurred in 2014 and 2015 enhanced the contribution of PD to SR.

Hirano *et al*. (2014) estimated smaller PD values than were found in our results (382 and 362 g C m^{-2} y^{-1} with minimum GWLs of -0.82 and -0.55 m in 2004–2005 and 2005–2006, respectively) from the same DB site using automated closed-chamber systems. After ten years, PD was much higher (646 and 748 g C m^{-2} y^{-1} with minimum GWLs of -0.81 and -1.53 m in 2014 and 2015, respectively), suggestive of the effects of both longer and stronger dry seasons (2014 and 2015) and a new drainage canal nearby. Applying the PD-prediction equation to data from DB by Hirano *et al*. (2014) for 2014 and 2015 resulted in PD values of 637 and 1093 g C m^{-2} y^{-1}, almost equivalent to and much greater than our predictions in 2014 and 2015, respectively (Table 4). The differences between the two predictions for 2015 may be attributed to the much higher GWL during their observation period (minimum: -0.8 m) than our observation year in 2015 (minimum: -1.52 m). In other words, they did not include PD data associated with lower GWLs in their equation. In addition, after Hirano *et al*. (2014) completed their measurements, the site was burned in 2009, which changed the physical and chemical properties of the surface peat. The predicted PD based on subsidence measurement (Hooijer *et al*., 2014) in the same region after the fire of 2009 (450 g C m^{-2} y^{-1}) was also

comparable with the results of Hirano *et al*. (2014) and our study.

The PD values at our sites for the same period until the end of November 2015 (UF: 755 ± 99, DF: 822 ± 24, DB: 747 ± 37 g C m^{-2} y^{-1}) were much lower than the annual PD at a rubber plantation site (1408 g C m^{-2} y^{-1} in December 2014 to December 2015; Wakhid *et al*., 2017). This can probably be attributed to the lower GWL due to drainage and the higher bulk density of the peat after compaction at the rubber plantation (Table 4). Moreover, fertilizer application at plantations could also explain this difference (Jauhianinen *et al*., 2014; Comeau *et al*., 2016) due to improvements in peat nutrient conditions, which would support microbial activity.

4.2.2 Research on heterotrophic respiration

Table 4 shows a comparison of the annual PD (or SR-RR) in tropical peat reported in the literature for several types of plantations, forests, and a burned site. The PD values at our sites were lower than those of most plantation sites in Indonesia (oil palm: 930–1042 g C m^{-2} y^{-1} [Dariah *et al*., 2014], 1800 g C m^{-2} y^{-1} [Husnain *et al*., 2014]; acacia: 2182 g C m^{-2} y^{-1} [Jauhianinen *et al*., 2012]; and rubber: 1418 g C m^{-2} y^{-1} [Husnain *et al*., 2014] and 1408 g C m^{-2} y^{-1} [Wakhid *et al*., 2017]) and comparable to the results from Sarawak, Malaysia (693, 762, and 993 g C m^{-2} y^{-1} at oil palm, sago, and mixed forest sites, respectively [Melling *et al*., 2013]). The greater PD at Indonesian plantations was partly

due to the lower GWL there than at the other plantation sites (Table 4), where GWLs are usually lower due to drainage canals. The significantly larger PD values at DB after the canal excavation than before the excavation suggested that the decrease in GWL from waterlogged conditions enhanced PD in the burned area. Moreover, this suggests that increasing the number of drainage canals enhances CO_2 efflux in areas of burned peat. Stable PD ranges are expected at plantations that maintain GWLs in the drained condition ($\leq$-0.6 m). By contrast, larger variation in PD are expected at non-plantation sites without water management (i.e., larger GWL variation), such as our observation sites. The PD values at an acacia plantation and several oil palm plantations were more than double our results, which can partially be attributed to the lower C/N ratio at the acacia plantation with its richer organic matter (Hergoualc'h and Verchot, 2011) or the positive effect of fertilizer on CO_2 emissions, particularly in agricultural peatland (Jauhiainen *et al*., 2014). In addition, Könönen *et al*. (2016) analyzed peat in the same area in Central Kalimantan and reported that the distribution of peat carbon compounds, which is related to labile and recalcitrant compounds, can be altered as a result of both drainage and fires. This underlines the importance of measuring both the physical conditions and peat chemical condition (nutrients, carbon compounds, etc.) in PD studies.

5. Conclusions

We measured soil CO_2 efflux due to oxidative PD in trenching plots using the closed-chamber method at three sites representing different types of land use (UF, DF, and DB) on tropical peat in Central Kalimantan, Indonesia. PD exhibited seasonality, and was lower in the wet (high-GWL) season and higher in the dry (low-GWL) season. The mean PD values among the three daily measurements during the observation dates over the 2 years of the study did not differ significantly at the three study sites. PD showed a quadratic convex upward relationship with GWL at UF and DF. At DF, the 3-month mean GWL explained PD better than did the daily GWL. At DB, the relationship between PD and GWL differed between the dry and wet seasons. The difference in these relationships was probably due to changes in the physical characteristics of peat and hydrological conditions due to drainage and peat fires. PD was estimated from GWL data at all sites. The annual PD was estimated for the 2 observation years (2014 and 2015), which experienced drier-than-normal conditions. At DF, where the GWL remained below the peat surface throughout the observation period, there were no differences in annual PD between the 2 years. The more variable GWL conditions at UF and DB resulted in yearly differences in PD, and much greater PD values were observed at both sites under the severely dry conditions in 2015, a strong El Niño year. The annual PD values at our sites were much lower than those reported at plantations (e.g., oil palm, rubber, and acacia) in

previous reports on tropical peatland, although our sampling period (2014–2015) had the

driest conditions among the 10 years during which these studies took place. Besides the

changes in GWL due to changes in land use, both bulk density, which can affect both

water permeability and oxygen supply to the deeper zone, and litter and fertilizer input,

which can affect nutrient conditions, were important determining factors for PD. This

underlines the importance of measuring both the physical and chemical characteristics of

peat in PD studies. Finally, the prediction of the seasonal variation in PD suggested that

the increased dryness of the seasons stemming from climate change and the expansion of

plantations in peat areas could enhance PD in both pre- and post-burned tropical peatlands.

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