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# How do land use practices affect methane emissions from tropical peat ecosystems?

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ABSTRACT

Wetlands in Southeast Asia are thought to be one of the greatest sources of methane ($CH_4$) to the atmosphere. Tropical peatlands are typical in Southeast Asia, and store an enormous amount of soil organic carbon. However, chamber studies of soil $CH_4$ flux have reported that $CH_4$ emissions from tropical peatlands in Southeast Asia are almost negligible. Recently, it was reported that some tree species growing in peat swamp forests emit considerable $CH_4$ from their stems. Thus, ecosystem-scale flux measurement is essential to quantify the $CH_4$ balance of tropical peat ecosystems. In this 3-year study (February 2014 to January 2017), using the eddy covariance technique, we measured the net ecosystem exchange of $CH_4$ ($F_{CH4}$) above three different tropical peat ecosystems in Sarawak, Malaysia. The three sites were an undrained peat swamp forest (UF), a relatively disturbed secondary peat swamp forest (DF) and an oil palm plantation (OP). The weekly mean $F_{CH4}$ was positively correlated to the groundwater level (GWL) in the UF and DF. In contrast, the $F_{CH4}$ was independent of GWL in the OP, in which GWL was lowered by drainage. The monthly mean $F_{CH4}$ was always positive, even in the drained OP. Mean annual $CH_4$ emissions ($\pm$ 1 SD) were 8.46 $\pm$ 0.51, 4.17 $\pm$ 0.69, and 2.19 $\pm$ 0.21 g C $m^{-2}$ $year^{-1}$ in the UF, DF, and OP, respectively. The inter-site differences in emissions were explained by a significant positive exponential relationship ($P < 0.001$) with the GWL. This relationship indicates that the conversion of a peat swamp forest to an oil palm plantation decreases $CH_4$ emissions, because the land conversion is accompanied by drainage. The OP, which was drained to –62 cm on average, still functioned as a small $CH_4$ source, probably because of the high $CH_4$ emissions from ditches.

## 1. Introduction

The atmospheric concentration of methane ($CH_4$) has increased by 150% since the pre-industrial era, rising from 722 ppb in 1750 to 1803 ppb in 2011 (IPCC, 2013). Wetlands are the largest natural source of global $CH_4$ emissions, responsible for about one-third of total emissions (Zhang et al., 2017); a bottom-up approach showed a large range of global $CH_4$ emissions from natural wetlands (177 – 284 Tg $CH_4$ $year^{-1}$) (Kirschke et al., 2013). Tian et al. (2015) reported that the tropics (30°N–30°S) emit about 80% of all global $CH_4$ emissions. Zhang et al. (2017) estimated that tropical wetlands will remain the world's largest natural source, and be responsible for about 53.2 $\pm$ 0.7% of $CH_4$ emissions by the end of the 21st century under the RCP 8.5 scenario, despite decreasing wetland areas and increasing drought frequency in the tropics. In Southeast Asia, $CH_4$ emissions from wetlands were estimated to be up to 26 Tg $CH_4$ $year^{-1}$ (Kirschke et al., 2013).

Tropical peatlands are common in Southeast Asia, with total areas of 20.7 Mha in Indonesia and 2.6 Mha in Malaysia (Page et al., 2011). Tropical peat has accumulated over millennia, resulting in a huge carbon pool (Yu et al., 2010; Dommain et al., 2011) consisting mainly of slightly or partially decayed trunks, branches, and roots of swamp trees (Melling and Hatano, 2004). Most tropical peatlands are located in coastal lowlands with high groundwater levels (GWLs). Given their large soil carbon stocks, high GWLs, and high temperatures, tropical peatlands could potentially function as a significant source of $CH_4$ to the atmosphere.

The topography of tropical peatlands is generally dome-shaped, with greater peat depths toward the center of the peat dome. In Borneo, peat hydrology strongly influence species compositions and vegetation

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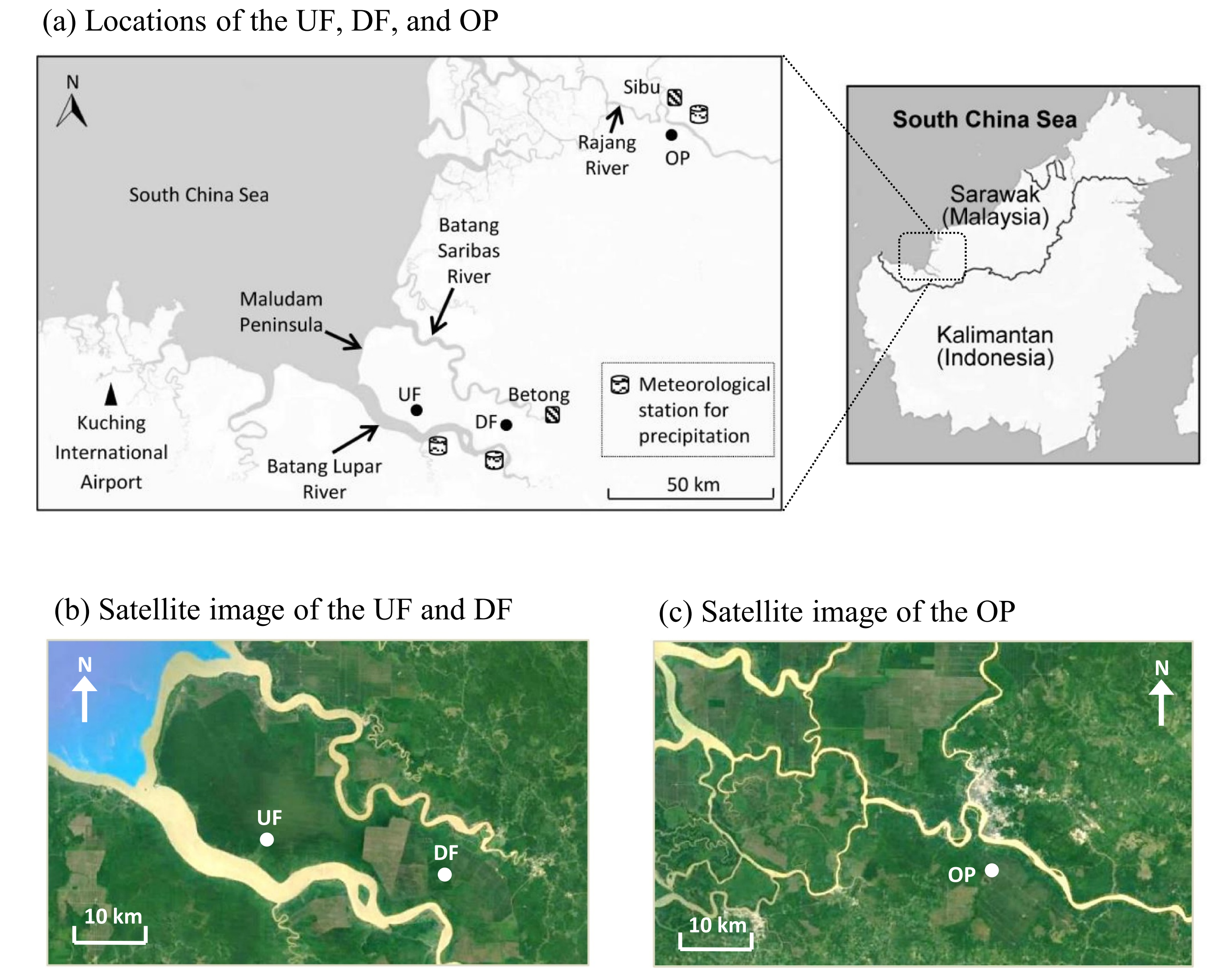


**Fig. 1.** (a) Map of the study sites, and satellite (Google Earth) images of the (b) undrained peat swamp forest (UF), relatively disturbed secondary peat swamp forest (DF), and (c) oil palm plantation (OP).

structures, leading to the formation of different zonal communities (Anderson, 1964). Six zonal communities of forest types have been reported for peat swamp forests in Sarawak, Malaysia, with the three main forest types being Mixed Peat Swamp, Alan, and Padang Alan (Anderson, 1961). Different zonal communities have also been reported from inland peatlands in Central Kalimantan, Indonesia (Page et al., 1999). However, the long-term peat accumulation rates of coastal peatlands were much higher than those of inland peatlands (Dommain et al., 2011, 2014).

Nowadays, however, the conversion of tropical peat swamp forests (PSFs) is widespread, and PSFs are also threatened by deforestation (e.g., Jauhiainen et al., 2012; Carlson et al., 2012; Gaveau et al., 2014). The conversion of PSFs into monoculture plantations of oil palm or pulpwood has become a global concern (e.g., Melling et al., 2005b; Germer and Sauerborn, 2008; Agus et al., 2009; Gaveau et al., 2014; Carlson et al., 2015; Miettinen et al., 2017). Land conversion is accompanied by drainage, and results in a lower GWL and higher oxidative peat decomposition rate (Hirano et al., 2009; Jauhiainen et al., 2012). In contrast, drainage thins the anaerobic soil layer, and could reduce $CH_4$ emissions (Melling et al., 2005a).

To date, soil $CH_4$ flux has been measured in tropical peatlands, including several types of PSF, using the manual chamber technique (Inubushi et al., 2003; Hadi et al., 2005; Jauhiainen et al., 2005; Melling et al., 2005a; Hirano et al., 2009). Field studies have reported that PSFs are $CH_4$ sources with annual emissions of 0.018–4.4 g C m$^{-2}$ year$^{-1}$, and oil palm plantations on peat are small sinks with an annual uptake of –0.015 g C m$^{-2}$ year$^{-1}$. However, the soil chamber technique is insufficient to quantify $CH_4$ emissions from a PSF because $CH_4$ is not only emitted from the soil surface, but also from tree stems (Pangala et al., 2013). In addition, it is difficult to quantify ecosystem-scale flux from soil chamber measurements with limited spatial replications of the heterogeneous hummock and hollow microtopography (Dislich et al., 2017). Additionally, periodic chamber measurements conducted only during the daytime might underestimate peat $CH_4$ emissions because of a distinct diurnal variation in soil gas efflux, which is attributable to the chamber technique itself (Ishikura et al., 2018). The eddy covariance technique is appropriate to measure the ecosystem-scale flux of trace gases, including $CH_4$, and is widely performed (e.g., Hanis et al., 2013; Nadeau et al., 2013; Olson et al., 2013; Song et al., 2015; Fortuniak et al., 2017) using a newly developed open-path $CH_4$ analyser (LI-7700, McDermitt et al., 2011). Regarding tropical PSFs, however, the application of the eddy covariance technique for $CH_4$ flux is still limited to two studies in Malaysia (Wong et al., 2018; Tang et al., 2018), and one in Indonesia (Sakabe et al., 2018). Wong et al. (2018) found that ecosystem-scale $CH_4$ emissions from an undrained PSF in Sarawak, Malaysia were controlled by the GWL, similarly to in chamber studies, whereas the annual $CH_4$ emissions determined by the eddy covariance technique were much larger than those determined by the soil chamber technique.

Tropical peatland $CH_4$ emissions may play an increasing role in the future atmospheric growth of $CH_4$. In this study, we compared $CH_4$ fluxes from an undrained PSF (UF), a relatively disturbed secondary PSF (DF), and an oil palm plantation (OP) established on tropical peat. The $CH_4$ flux was measured continuously above the canopy using the eddy covariance technique for 3 years from February 2014 to January 2017. We quantified and compared the annual $CH_4$ balances of the three peat ecosystems. The carbon dioxide ($CO_2$) balance of DF has been reported previously, and thus we also determined the net greenhouse gas balance of $CO_2$ and $CH_4$ in DF. Furthermore, we tested the following hypotheses: (i) drainage reduces $CH_4$ emissions, and (ii) tropical peatland changes from a source to a sink of $CH_4$ after land conversion from a PSF to an oil palm plantation.

## 2. Materials and methods

### 2.1. Study site

This study was conducted in three different coastal peat ecosystems (Dommain et al., 2011): an undrained PSF (1° 27′ N, 111° 8′ E), a relatively disturbed secondary PSF (1° 23′ N, 111° 24′ E), and an oil palm plantation (2° 11′ N, 111° 50′ E) in Sarawak, Malaysia (Fig. 1). The UF and DF are located about 29 km apart in the Maludam Peninsula, whereas the OP is in Sibu, more than 100 km away from the peninsula.

All study sites were located on flat terrain with peat depths of at least 10 m (Table 1). The UF is part of the Maludam National Park (43,147 ha), which has been gazetted since 2000 as a totally protected PSF area with minimal forest disturbance. Thus, we treated the UF as the most natural PSF ecosystem in Sarawak. The UF is in an Alan Batu forest, where the dominant tree species is *Shorea albida*. In the DF, the forest has been selectively logged and regrown. The DF is at the border of Alan Bunga and Padang Alan forests, and the surrounding DF has been converted from PSF to oil palm plantations; consequently, the GWL has decreased compared to that of the undisturbed PSF. The dominant tree species are *Litsea* spp. and *Shorea albida*. The microtopographies of the UF and DF consist of hollows and hummocks covered mostly with leaf litter. In the OP, a PSF was converted to an oil palm (*Elaeis guineensis* Jacq.) plantation in 2004. During land preparation, the peat was compacted to increase the soil bulk density to prevent palm trees from leaning and toppling, and also to increase the soil moisture holding capacity (Melling et al., 2008). Ditches and water gates were installed to control the GWL.

The canopy was the highest in the UF and followed by the DF and OP (Table 1). Both the UF and DF have uneven and dense canopies. However, the canopy of the UF was thinner than that of the DF, and the UF had more prominent emergent trees. The canopy of the OP was sparse with gaps between palm trees, and almost even in height. At each site, plant area index (PAI) has been measured monthly since 2013 at 20 points (1.3 m height) around the tower using a plant canopy analyser (LAI-2200, Li-Cor Inc., Lincoln, NE, USA). The mean PAI of UF, DF, and OP were 6.4, 7.9, and 3.7 $m^2\ m^{-2}$, respectively. The bulk density of surface peat (0–5 cm) was two times higher at the OP than at the UF and DF because the peat was compacted (Table 1). As observed from the peat profiles, the peat was studded with many undecomposed woody fragments and cavities in the UF and DF, whereas it was more decomposed and consolidated in the OP. Further information is provided by Wong et al. (2018) for the UF, Kiew et al. (2018) for the DF, and Ishikura et al. (2018) for the OP.

The climate of the region is equatorial and characterized by consistently high temperatures, high humidity, and abundant precipitation all year round. Mean annual precipitations (2005–2014) at local meteorological stations near the UF, DF, and OP were 3201 ± 614, 3358 ± 465, and 2797 ± 224 mm $year^{-1}$ (mean ± 1 standard deviation [SD]), respectively (Fig. 1a). The precipitation was generally higher in December–January at all sites. The mean annual air temperature in the same period was 26.5 ± 0.2 °C at the nearest meteorology station, in Kuching International Airport.

### 2.2. Eddy flux and meteorological measurement

Methane flux was measured above the canopies by the eddy covariance technique (McDermitt et al., 2011), along with $CO_2$, water vapor, and heat fluxes, beginning in 2012. Flux sensors were mounted on towers at the heights of 41 m in the UF and DF and 21 m in the OP. Fetches of UF, DF, and OP were at least 600, 1200, and 4000 m long in all directions, respectively. At each site, the flux measurement system consisted of a 3D sonic anemometer/thermometer (CSAT3; Campbell Scientific Inc., Logan, UT, USA), an open-path $CO_2$/$H_2O$ analyser (LI-7500A; Li-Cor Inc., Lincoln, NE, USA), and an open-path $CH_4$ analyser (LI-7700; Li-Cor Inc.). These sensors were installed at the tip of a 1 m-long boom projecting toward the prevailing wind direction. The prevailing wind direction was southeast for all three sites. The sensor separation between the CSAT3 and LI-7700 units was between 38 and 60 cm. Sensor signals were sampled at 10 Hz using a datalogger (CR3000; Campbell Scientific Inc.). The system was powered by solar energy. The lower window of the $CH_4$ analyser was automatically cleaned when the relative signal strength indicator (RSSI) dropped below 20%. In addition, the upper and lower windows were manually cleaned twice per month using rain repellent (Rain-X) and tissue paper (Kimwipe). Fig. 2 shows the seasonal variations in monthly relative signal strength indicator (RSSI) of each site. The monthly RSSI were ensemble averaged for the common period of 3 years from February 2014 to January 2017. The monthly RSSI were always below 55% at all sites and were always lower in the OP than in the UF and DF. The RSSI were relatively low in comparison to a study in temperate climate using similar open-path $CH_4$ analyser (Dengel et al., 2011). The low RSSI were mainly due to frequent rainfall and dew condensation around the mirrors of the analyser, and maintaining high RSSI (i.e., high data quality) in the tropics is very challenging.

At each site, the solar radiation, air temperature, and relative humidity were measured on the tower, at the same height as the $CH_4$ analyser. The solar radiation was measured using a radiometer (CNR4, Kipp and Zonen, Delft, the Netherlands). The air temperature and relative humidity were measured using temperature and relative humidity probes (CS215, Campbell Scientific Inc.) installed in a 6-plate solar radiation shield (41,303-5A, Campbell Scientific Inc.). Precipitation was measured in a nearby open space using a tipping-

**Table 1**
Site information on the undrained peat swamp forest (UF; 1° 27′ N, 111° 8′ E), relatively disturbed secondary peat swamp forest (DF; 1° 23′ N, 111° 24′ E), and oil palm plantation (OP; 2° 11′ N, 111° 50′ E).

| Study site | Elevation m.s.l (m) | Dominant tree species | Tree density (trees $ha^{-1}$) | Plant area index ($m^2\ m^{-2}$) | Canopy height (m) | Peat depth (m) | Peat bulk density (g $cm^{-3}$)* | Reference |
|---|---|---|---|---|---|---|---|---|
| UF | 10 | *Shorea albida* | 1173 | 6.4 | 35 | 10.0 | 0.11 | Wong et al. (2018) |
| DF | 9 | *Litsea* spp. *Shorea albida* | 1990 | 7.9 | 25 | 10.0 | 0.12 | Kiew et al. (2018) |
| OP | 6 | *Elaeis guineensis* Jacq. | 153 | 3.7 | 8 | 12.7 | 0.24 | Ishikura et al. (2018) |

* 0–5-cm-thick surface peat.

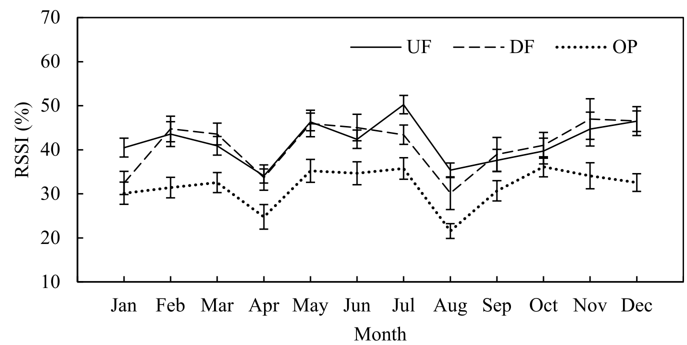


**Fig. 2.** Monthly relative signal strength indicator (RSSI) from February 2014 to January 2017 in the undrained peat swamp forest (UF), relatively disturbed secondary peat swamp forest (DF), and oil palm plantation (OP). Vertical bars denote standard errors.

bucket rain gauge (TE525, Texas Electronics). Soil temperature was measured at a depth of 5 cm using a platinum resistance thermometer (C-PTWP, Climatec, Tokyo, Japan). Soil moisture was measured in the top 30 cm of the soil using a time domain reflectometry (TDR) sensor (CS616, Campbell Scientific Inc.). All of the meteorological variables above were measured every 10 s and recorded every 5 min. The GWL was measured by a piezometer (HOBO, Onset, Bourne, MA, USA) and recorded every 30 min A positive GWL represents the water surface to be aboveground, and vice versa. Missing GWL data were gap-filled using a tank model (Sugawara, 1979).

### 2.3. Data processing

The half-hourly mean $CH_4$ flux was calculated using Flux Calculator software (Ueyama et al., 2012); raw data were processed according to the following procedures: (1) despiking (Ueyama et al., 2012), (2) double rotation for tilt correction (Wilczak et al., 2001), (3) block averaging, and (4) high frequency loss correction due to path-averaging and sensor separation (Massman, 2000, 2001). The air density fluctuations (Webb et al., 1980) and the spectroscopic effect of variations in the $CH_4$ absorption line shape (Iwata et al., 2014; Burba et al., 2019) were corrected for $CH_4$ flux. The spectroscopic effect was incorporated into the Webb-Pearman-Leuning density term (Li-Cor Inc., 2010; McDermitt et al., 2011) as follows:

$$CH_4\ flux = A\left\{\overline{w'q'_{cm}} + B\mu\frac{\overline{q_{cm}}}{\overline{q_d}}\overline{w'q'_v} + C\left(1+\mu\frac{\overline{q_v}}{\overline{q_d}}\right)\frac{\overline{q_{cm}}}{\overline{T}}\overline{w'T'}\right\} \tag{1}$$

where $w'q'_{cm}$ is the covariance of the vertical wind velocity ($w$) and the uncorrected $CH_4$ mass density ($q_{cm}$), $\mu$ is the ratio of molecular weight of dry air to water vapor, $q_d$ is the dry air mass density, $w'q'_v$ is the covariance of $w$ and the $H_2O$ mass density ($q_v$), and $w'T'$ is the covariance of $w$ and the air temperature ($T$). The bars denote the time averages over measurement interval. The A, B, and C are dimensionless factors; $A$ arises from the correction of spectroscopic effects of temperature, pressure, and water vapor on $CH_4$ density; $B$ represents the spectroscopic corrections to the latent heat flux term for pressure and water vapor; and $C$ represents the spectroscopic corrections to the sensible heat flux term for temperature, pressure, and water vapour (Li-Cor Inc., 2010; Sakabe et al., 2018). Table 2 shows the means of half-hourly measured $CH_4$ fluxes calculated before and after spectroscopic corrections from February 2014 to January 2017. The mean $CH_4$ fluxes increase at least 39% after the spectroscopic corrections.

**Table 2**
Means of half-hourly measured $CH_4$ fluxes before and after spectroscopic corrections from February 2014 to January 2017.

| Study site | Before correction (nmol $m^{-2}$ $s^{-1}$) | After correction (nmol $m^{-2}$ $s^{-1}$) |
|---|---|---|
| UF | 17.44 | 24.28 |
| DF | 8.26 | 12.87 |
| OP | 2.58 | 7.70 |

The net ecosystem $CH_4$ exchange ($F_{CH4}$) was calculated as the sum of eddy $CH_4$ flux and storage change (Wong et al., 2018). The $CH_4$ storage change was derived from the change in $CH_4$ concentration above the canopy measured with the open-path $CH_4$ analyser. Positive $CH_4$ flux values represent release from the ecosystem, and vice versa.

### 2.4. Quality control

A series of quality control procedures were applied to eliminate low-quality $F_{CH4}$ data. First, a RSSI threshold of 20% (Wong et al., 2018) was used to exclude low-quality data due to dew condensation, rain, dirty windows, etc. Then, $F_{CH4}$ data were screened according to stationary and integral turbulence tests (Foken and Wichura, 1996), a high moment test (Vickers and Mahrt, 1997; Mano et al., 2007), and the median absolute deviation around the median (Papale et al., 2006). In addition, we tried to determine the friction velocity ($u^*$) threshold to remove low-quality $F_{CH4}$ data recorded in low-turbulence conditions (Long et al., 2010; Wong et al., 2018). The $F_{CH4}$, eddy $CH_4$ flux, and storage change were sorted into 10 deciles by $u^*$ (Fig. 3). The average ± standard errors for $F_{CH4}$, eddy $CH_4$ flux, and storage change were calculated for each of the 10 deciles. The $u^*$ threshold was determined by the lowest $u^*$ of the decile whose corresponding averaged $F_{CH4}$ was statistically indistinguishable from plateau-averaged $F_{CH4}$ (Saleska et al., 2003; Hirano et al., 2007; Aubinet et al., 2012). A $u^*$ threshold of 0.14 $ms^{-1}$ (Tukey's HSD, $P < 0.05$) was determined for the UF, whereas the $F_{CH4}$ in DF and OP were independent of $u^*$. In UF, all $F_{CH4}$ data with corresponding $u^*$ at or below 0.14 $ms^{-1}$ were excluded from analyses.

### 2.5. Gap filling

Three years of data from February 2014 to January 2017 were used for analyses. After the quality control, the survival rates of $F_{CH4}$ data were 30%, 34%, and 29% for the UF, DF, and OP, respectively. The survival rates were much higher than the rates (15.7–17.4%) in a study using similar open-path $CH_4$ analyser in Central Kalimantan, Indonesia (Sakabe et al., 2018). Numerous $F_{CH4}$ gap-filling methods have been proposed in literature, but no standard method has been widely accepted due to imperfection of each method (Dengel et al., 2013; Nemitz et al., 2018; Kim et al., 2019). In our previous study, we used multiple imputation and mean diurnal variation (MDV) methods to fill the gaps in $F_{CH4}$ data (Wong et al., 2018). Both methods perform well in the estimation of annual $F_{CH4}$. The complete GWL data set without missing data was used in multiple imputation method for the gap filling. In this study, due to the missing data in GWL, we adopted only the MDV method (Falge et al., 2001; Sigrid Dengel et al., 2011; Hommeltenberg et al., 2014; Jha et al., 2014; Gao et al., 2015; Wong et al., 2018) to gap fill the $F_{CH4}$. In this method, missing half-

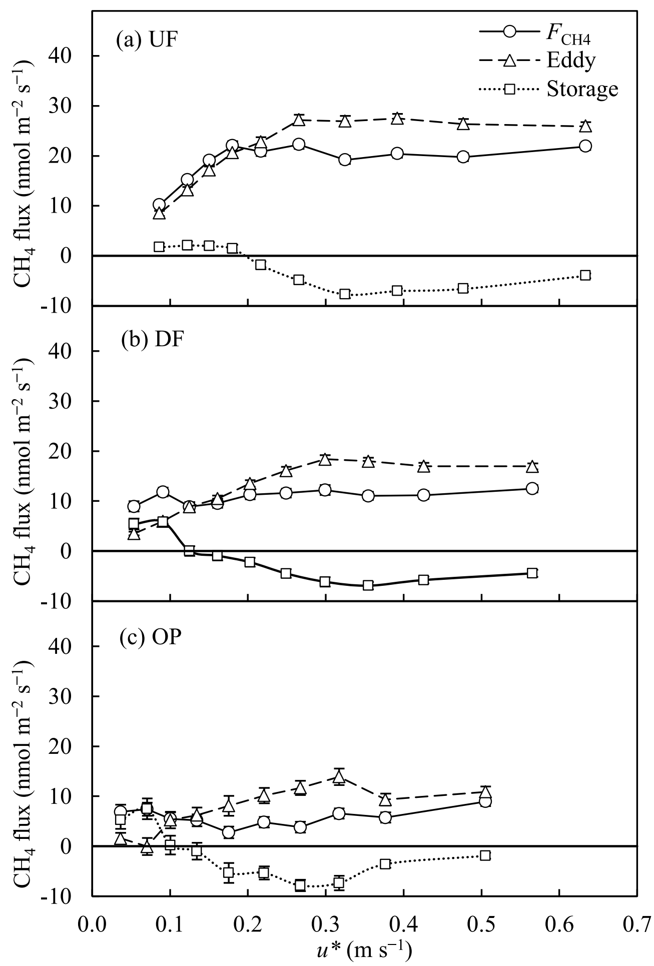


**Fig. 3.** Relationships between $CH_4$ fluxes (net ecosystem $CH_4$ exchange [$F_{CH4}$], eddy $CH_4$ flux, and $CH_4$ storage change) and friction velocity ($u$*) for 24 h of data from the (a) undrained peat swamp forest (UF), (b) relatively disturbed secondary peat swamp forest (DF), and (c) oil palm plantation (OP). Vertical bars denote standard errors. Flux data were sorted by $u$* and separated into decile groups.

hourly $F_{CH4}$ and eddy flux data were replaced with a value at the same time from the mean diurnal variation calculated using a moving window of 83 days. Then, the annual $F_{CH4}$ was calculated using the gap-filled data. The annual period was defined from February 1 to January 31.

### 2.6. Net greenhouse gas balance calculation

We determined the net greenhouse gas balance from $CO_2$ and $CH_4$ fluxes in DF using sustained-flux global warming potential (SGWP) (Neubauer and Megonigal, 2015). Recently, Kiew et al. (2018) reported the annual $CO_2$ balance of the DF from a 4-year long measurement (2011–2014) using the eddy covariance technique. In their study, the eddy $CO_2$ flux was measured at the height of 41 m, and the $CO_2$ storage change was estimated from $CO_2$ concentrations measured at 41, 21, 11, 3, 1, and 0.5 m. The low-quality $CO_2$ flux data in their study were filtered out using the median absolute deviation around the median (Papale et al., 2006) and the deviation from mean diurnal variation. The gaps in $CO_2$ flux were filled using the marginal distribution sampling method (Reichstein et al., 2005).

The annual $F_{CH4}$ of DF can be converted into a $CO_2$ equivalent unit using an SGWP factor of 45 (Neubauer and Megonigal, 2015). This scaling factor represents the SGWP for $CH_4$ over a timescale of 100 years. A net greenhouse gas balance was then calculated for the DF as the sum of the annual $CO_2$ balance and converted annual $F_{CH4}$.

## 3. Results and discussion

### 3.1. Environmental variables

In all sites, precipitation was generally higher in December or January in each annual period (Fig. 4a). This seasonal variation was similar to that of long-term records from 2005. Interannual variations in precipitation in the UF and OP were different from that in the DF (Table 3); the highest annual precipitation was recorded in the second annual period (Feb. 15–Jan. 16) in the UF and OP, whereas it was recorded in the third annual period in the DF (Feb. 16–Jan. 17). However, the annual precipitation was not significantly different among sites ($P > 0.05$, ANOVA). In all sites, the mean annual precipitation for the three annual periods was lower than long-term mean annual precipitation (2005–2014), which was mainly due to an El Niño event in 2014–2016.

Seasonal variations in the monthly mean GWL (Fig. 4b) were similar to those in the monthly precipitation (Fig. 4a) in all sites. GWL and precipitation were positively correlated in each site ($P < 0.001$), including the water-managed OP. The monthly GWL ranged between −30 and +12 cm in the UF. In normal years, the GWL in the UF remained near to or above the soil surface. However, because of limited precipitation (44 mm), the GWL dropped to −30 cm in July 2014. In the DF, the GWL was probably influenced by the water management of nearby oil palm plantations, which were about 1.2 km away. Consequently, the GWL of the DF varied from −51 to +0.2 cm, and was lower than that of the UF, except for between August and December 2014. In the OP, the monthly GWL was relatively stable, ranging between −80 and −45 cm. The effect of water management was apparent in this site, because the monthly GWL never rose above the soil surface and its variation was the narrowest of the three sites. Interannual variations in GWL and precipitation were similar to each other in UF and DF, whereas the GWL was significantly different among the sites ($P < 0.001$) (Table 3). The mean annual GWLs in the UF, DF, and OP were −4.9 ± 2.6, −20.8 ± 2.2, and −62.1 ± 4.0 cm, respectively.

The air temperature showed no clear seasonal variation among all sites (data not shown). The mean annual air temperatures in the UF, DF, and OP were 27.2 ± 0.17, 26.9 ± 0.32, and 26.2 ± 0.29 °C, respectively (Table 3), and were comparable to the long-term (2005–2014) mean air temperature of 26.5 ± 0.2 °C recorded at Kuching International Airport (Fig. 1). The air temperatures of the UF and DF were significantly higher than that of the OP ($P < 0.05$), though the difference was only within 1.0 °C on average.

### 3.2. Diurnal variations in $CH_4$ fluxes

The half-hourly $CH_4$ flux was ensemble averaged for each site for the 3 years (Fig. 5). The eddy $CH_4$ flux and $F_{CH4}$ were always positive in the UF and DF, and were always higher in the UF than in the DF. In the OP, the eddy $CH_4$ flux and $F_{CH4}$ were occasionally negative and lower than those in the UF. At all sites, the eddy $CH_4$ flux showed a positive peak in the early morning. However, the peak was much higher in the UF than in the DF and OP; the peak fluxes in the UF, DF, and OP were 87, 48, and 37 nmol m$^{-2}$ s$^{-1}$, respectively. In contrast, the $CH_4$ storage change showed a negative peak in the early morning at each site. These positive and negative peaks reflected the flush out of nocturnally-stored $CH_4$ below the forest canopy because of the increase in turbulent mixing after sunrise. The flush out lasted from 0700 to 1100 h. As for $F_{CH4}$, only the UF showed an obvious peak, with 59 nmol m$^{-2}$ s$^{-1}$ at 0800 h. The $CH_4$ storage change was calculated using only $CH_4$ concentrations at the top of the tower. Consequently, the $CH_4$ storage change would have been underestimated, especially in the UF with its tall forest canopy. Thus, a peak remained in $F_{CH4}$ in the UF because the apparent negative peak in the storage change was insufficient to

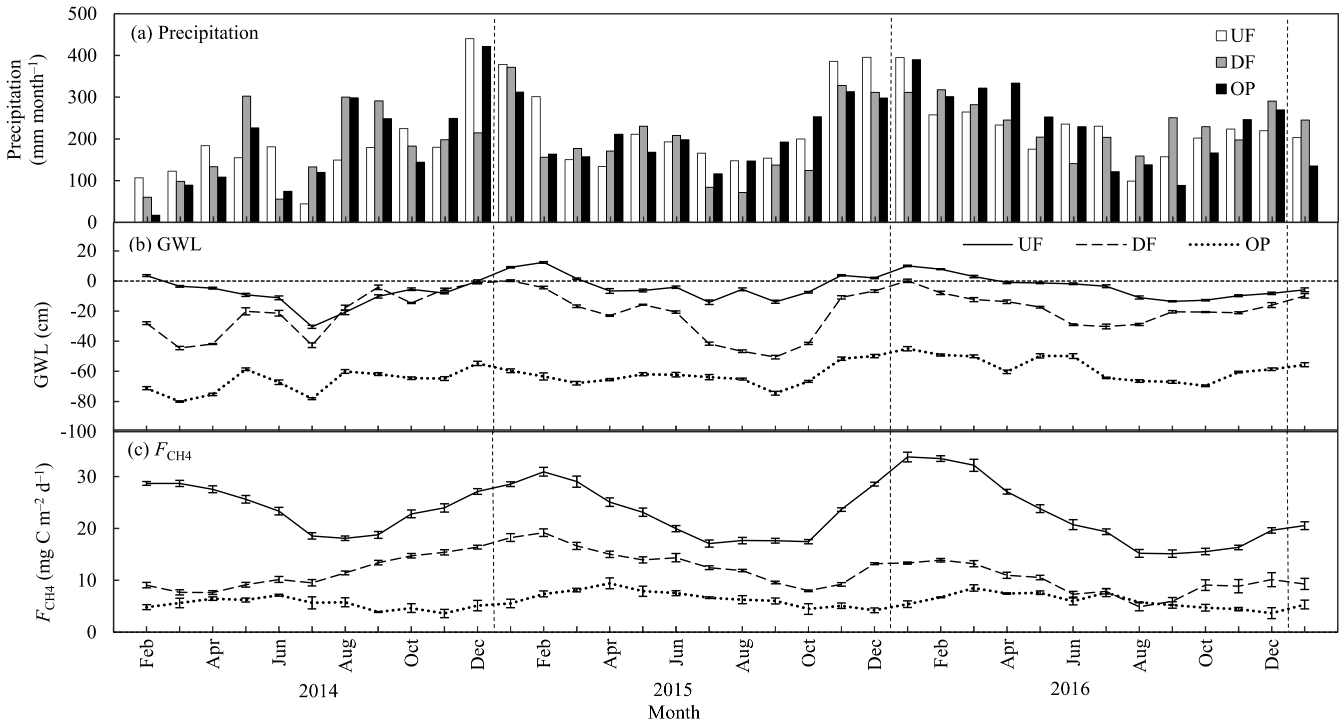

**Fig. 4.** Monthly (a) precipitation, (b) groundwater level (GWL), and (c) gap-filled daily net ecosystem $CH_4$ exchange ($F_{CH4}$) from February 2014 to January 2017 in the undrained peat swamp forest (UF), relatively disturbed secondary peat swamp forest (DF), and oil palm plantation (OP). Vertical bars denote standard errors.

**Table 3**
Annual precipitation, air temperature, groundwater level (GWL), and net ecosystem $CH_4$ exchange ($F_{CH4}$) in the undrained peat swamp forest (UF), relatively disturbed secondary peat swamp forest (DF), and oil palm plantation (OP) for 3 years. For the GWL, values in parentheses represent the range of monthly mean GWLs. Friction velocity ($u^*$) correction was applied for $F_{CH4}$ only in the UF. Different letters following the mean values in each column denote significant differences between the sites (Tukey's HSD, $P < 0.05$).

| Site | Annual period | Precipitation (mm year$^{-1}$) | GWL (cm) | Air temperature (°C) | $F_{CH4}$ (g C m$^{-2}$ year$^{-1}$) |
|---|---|---|---|---|---|
| UF | Feb. 14–Jan. 15 | 2346 | –7.6 (–30.4 to +9) | 27.1 | 8.87 |
| | Feb. 15–Jan. 16 | 2833 | –2.4 (–14.2 to +12.4) | 27.4 | 8.63 |
| | Feb. 16–Jan. 17 | 2503 | –4.8 (–13.5 to +7.9) | 27.2 | 7.89 |
| | Mean ± 1 SD | 2560 ± 249$^a$ | –4.9 ± 2.6$^a$ | 27.2 ± 0.17$^a$ | 8.46 ± 0.51$^a$ |
| DF | Feb. 14–Jan. 15 | 2341 | –20.2 (–44.5 to +0.2) | 26.6 | 4.35 |
| | Feb. 15–Jan. 16 | 2311 | –23.2 (–50.6 to +0.1) | 27.3 | 4.75 |
| | Feb. 16–Jan. 17 | 2766 | –19.0 (–30.2 to –7.9) | 26.9 | 3.41 |
| | Mean ± 1 SD | 2472 ± 254$^a$ | –20.8 ± 2.2$^b$ | 26.9 ± 0.32$^a$ | 4.17 ± 0.69$^b$ |
| OP | Feb. 14–Jan. 15 | 2309 | –66.4 (–80.1 to –54.8) | 25.9 | 1.96 |
| | Feb. 15–Jan. 16 | 2608 | –61.5 (–74.6 to –45) | 26.4 | 2.38 |
| | Feb. 16–Jan. 17 | 2605 | –58.5 (–69.7 to –49.1) | 26.4 | 2.23 |
| | Mean ± 1 SD | 2507 ± 172$^a$ | –62.1 ± 4.0$^c$ | 26.2 ± 0.29$^b$ | 2.19 ± 0.21$^c$ |

compensate for the positive peak in the eddy flux.

### 3.3. Response of $F_{CH4}$ to GWL

The influence of the GWL on the $F_{CH4}$ was examined using a regression analysis. To avoid biases due to the morning flush out (Fig. 5), the weekly means were used. The weekly means were calculated from the gap-filled data. The $F_{CH4}$ showed a significant exponential relationship with the GWL in both the UF ($R^2 = 0.422$; $P < 0.001$) and DF ($R^2 = 0.204$; $P < 0.001$) (Fig. 6).

In the UF and DF, the $F_{CH4}$ changed seasonally, following the rise and fall of the GWL (Fig. 4b and c), which affected $CH_4$ emissions by changing the stratification of methanogenesis and methanotrophy (Turetsky et al., 2008; Munir and Strack, 2014). The $F_{CH4}$ values of the UF and DF were found to be positively associated with the GWL (Fig. 6a and b), similar to previous studies conducted in tropical and temperate peatlands (Inubushi et al., 2005; Yang et al., 2014; Song et al., 2015). A high GWL thickens the saturated layer of the peat and restricts aeration. This condition increases methanogenesis, decreases methanotrophy, and thus increases the emission of $CH_4$ into the atmosphere. In contrast, a low GWL enhances soil aeration and stimulates $CH_4$ oxidation. A study in Central Kalimantan, Indonesia reported that the GWL boundary for soil $CH_4$ efflux/influx was –20 cm in an undrained PSF (Jauhiainen et al., 2005, 2008). In this study, however, the $F_{CH4}$ was always positive, even when GWLs were lower than –20 cm (Fig. 6a and b), probably attributed to $CH_4$ emissions from tree stems (Pangala et al., 2013; Covey and Megonigal, 2019).

In addition, the seasonal change in GWL may affect the amount of substrate for methanogenesis. After GWL drawdown, the soil organic matter in unsaturated layers is decomposed oxidatively, which results in a lack of substrate that could be consumed for methanogenesis when the GWL increases again (Kettunen et al., 1999; Waddington and Day, 2007). The GWL decreased considerably in July–August 2014 in the UF and in July–October 2015 in the DF (Fig. 4b). To test the above

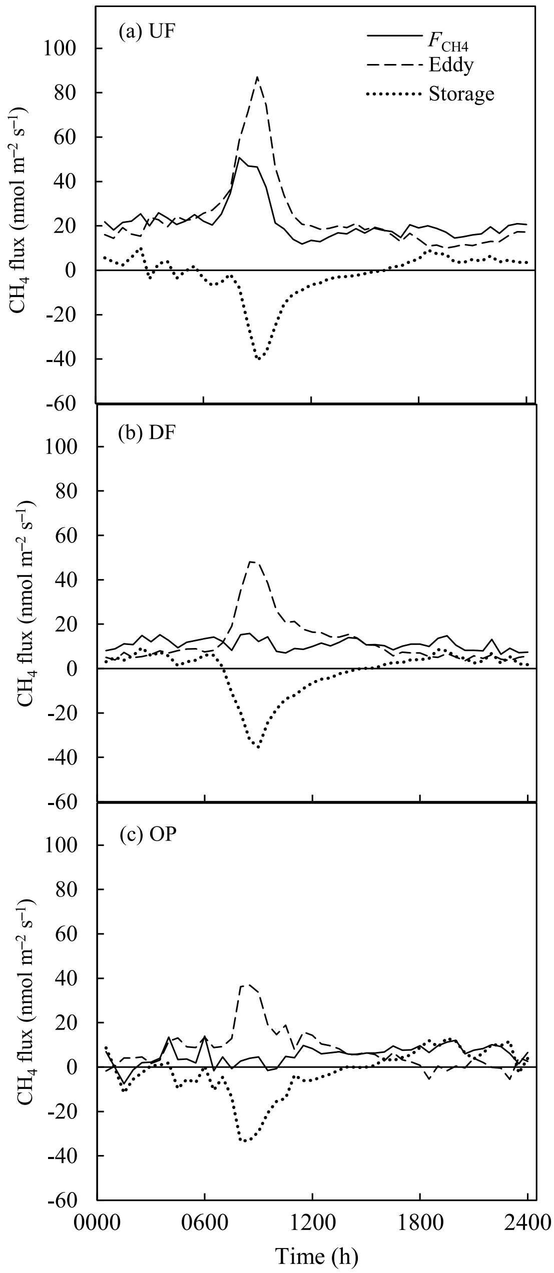


**Fig. 5.** Ensemble mean diurnal variations in net ecosystem $CH_4$ exchange ($F_{CH4}$), eddy $CH_4$ flux, and $CH_4$ storage change for 3 years in the (a) undrained peat swamp forest (UF), (b) relatively disturbed secondary peat swamp forest (DF), and (c) oil palm plantation (OP).

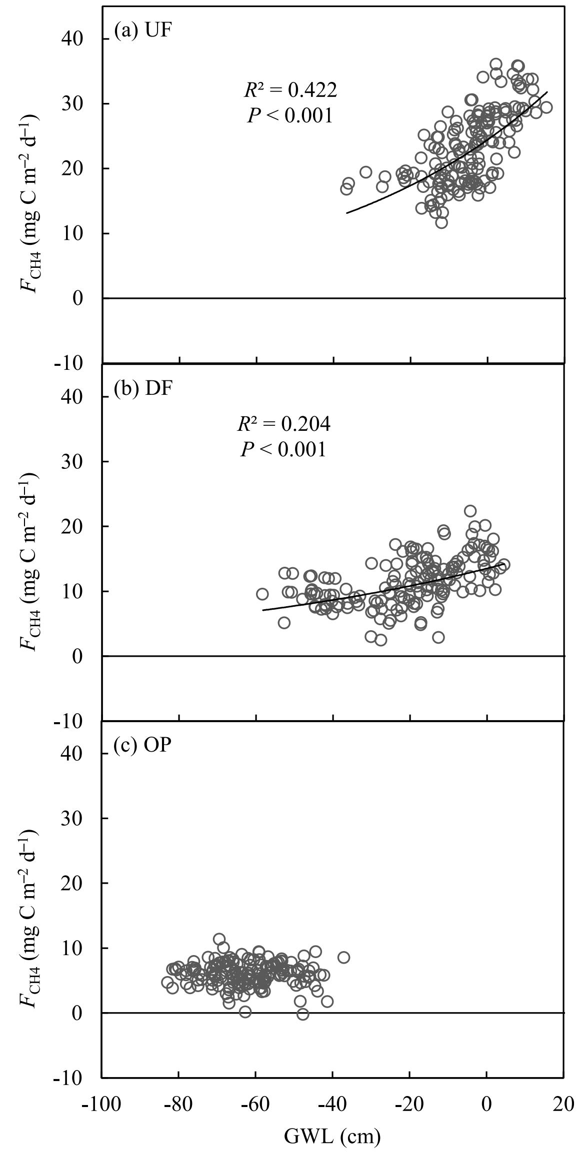


**Fig. 6.** Response of the net ecosystem $CH_4$ exchange ($F_{CH4}$) to changes in groundwater level (GWL) in the (a) undrained peat swamp forest (UF), (b) relatively disturbed secondary peat swamp forest (DF), and (c) oil palm plantation (OP). Weekly means were plotted. Exponential curves were drawn if the results were significant.

result, we compared the mean $F_{CH4}$ before and after the lowest GWL periods (Table 4). The mean $F_{CH4}$ was calculated under GWL conditions of −15 to 0 and −20 to −10 cm in the UF and DF, respectively, to eliminate the effect of the GWL itself. In both the UF and DF, the $F_{CH4}$ was significantly lower ($P < 0.01$) after GWL drawdown, despite the effect of GWL being removed. This difference suggests that enhanced oxidative decomposition during the dry period consumed substrate that could be used for $CH_4$ production when the GWL increased again. The relatively scatterings shown in Fig. 6a and b can probably be attributed to this hysteresis in the relationship between the $F_{CH4}$ and GWL.

### 3.4. Seasonal variations in $CH_4$ balance

The monthly mean gap-filled $F_{CH4}$ is shown in Fig. 4c. The monthly $F_{CH4}$ was always positive in all sites, indicating that they were continuous net $CH_4$ sources to the atmosphere. The range of $F_{CH4}$ variation was widest in the UF and narrowest in the OP. In the UF, DF, and OP, the ranges were 15.1–33.8, 4.9–19.2, and 3.6–9.4 mg C $m^{-2}$ $d^{-1}$, respectively. The monthly $F_{CH4}$ was positively correlated with the GWL in the UF ($R^2 = 0.59$; $P < 0.001$) and DF ($R^2 = 0.34$; $P < 0.001$). In the OP, however, no significant correlation was found, probably because of the narrow range in the GWL due to water management. These relationships are in accordance with those found using the weekly means (Fig. 6).

### 3.5. Comparison of $F_{CH4}$ among three sites

The annual $F_{CH4}$ is shown in Table 3. All annual values were positive. There was a significant difference in the annual $F_{CH4}$ among the sites ($P < 0.001$). The mean (± 1 SD) annual $F_{CH4}$ values were 8.46 ± 0.51, 4.17 ± 0.69, and 2.19 ± 0.21 g C $m^{-2}$ $year^{-1}$ for the UF, DF, and OP, respectively. The mean annual $F_{CH4}$ of the UF was double that of the DF and was about four times larger than that of the

**Table 4**
Mean $F_{CH4}$ ( ± 1 SD) of the undrained peat swamp forest (UF) and relatively disturbed secondary peat swamp forest (DF) before and after their respective lowest GWL periods: July–August 2014 for the UF and July–October 2015 for the DF. The mean $F_{CH4}$ was calculated from the daily mean $F_{CH4}$ in GWL conditions of –15 to 0 cm and –20 to –10 cm for the UF and DF, respectively. Different letters after $F_{CH4}$ denote significant differences between the periods in each site (Welch's *t*-test, $P < 0.01$).

| Site | Period | Number of days | GWL (cm) | Mean $F_{CH4}$ (nmol m$^{-2}$ s$^{-1}$) |
|---|---|---|---|---|
| UF | June 2014 (before) | 13 | –15 to 0 | 32.6 ± 8.04$^a$ |
| | September 2014 (after) | 17 | –15 to 0 | 10.5 ± 8.77$^b$ |
| DF | May–June 2015 (before) | 42 | –20 to –10 | 12.6 ± 7.76$^a$ |
| | November–December 2015 (after) | 6 | –20 to –10 | 4.17 ± 4.43$^b$ |

OP. The $u*$ correction was only applied to the $F_{CH4}$ of the UF. To examine the effect of $u*$ correction in the UF, the mean annual $F_{CH4}$ was also calculated without $u*$ correction to be 7.69 ± 0.29 g C m$^{-2}$ year$^{-1}$, which was smaller than that with $u*$ correction by 0.77 g C m$^{-2}$ year$^{-1}$ (9%). In addition, the mean annual eddy $CH_4$ fluxes was calculated without $u*$ correction to be 8.48 ± 0.30, 4.59 ± 0.50, and 2.96 ± 0.29 g C m$^{-2}$ year$^{-1}$ for the UF, DF, and OP, respectively. Annual accumulations of $F_{CH4}$ and eddy $CH_4$ flux could be equivalent because both the positive and negative values of $CH_4$ storage change compensated each other. Similarly, with $F_{CH4}$, the annual eddy $CH_4$ was significantly different among the sites ($P < 0.001$). Similar annual $CH_4$ balances obtained independently of $u*$ correction indicate that these tropical peat ecosystems functioned as net $CH_4$ sources.

To examine the differences among sites, the gap-filled $F_{CH4}$ was plotted against the GWL on monthly and annual bases (Fig. 7), including all data from the three sites. A significant exponential relationship was found on either a monthly ($P < 0.001$; $R^2 = 0.76$) or annual ($P < 0.001$; $R^2 = 0.88$) basis. The monthly mean $F_{CH4}$ increased sharply when the monthly mean GWL was above –20 cm. In addition, this relationship suggests that the $F_{CH4}$ was more than 20.4 mg C m$^{-2}$ d$^{-1}$ in the PSFs of Sarawak when the ground was flooded. On an annual basis, the annual $F_{CH4}$ might be 8.03 g C m$^{-2}$ year$^{-1}$ if the annual mean GWL was zero. A similar exponential relationship was reported in annual data for $CH_4$ flux and GWL from northern peatlands (Abdalla et al., 2016). This significant relationship indicates that the difference in $F_{CH4}$ among the three sites was mainly due to the difference in GWL.

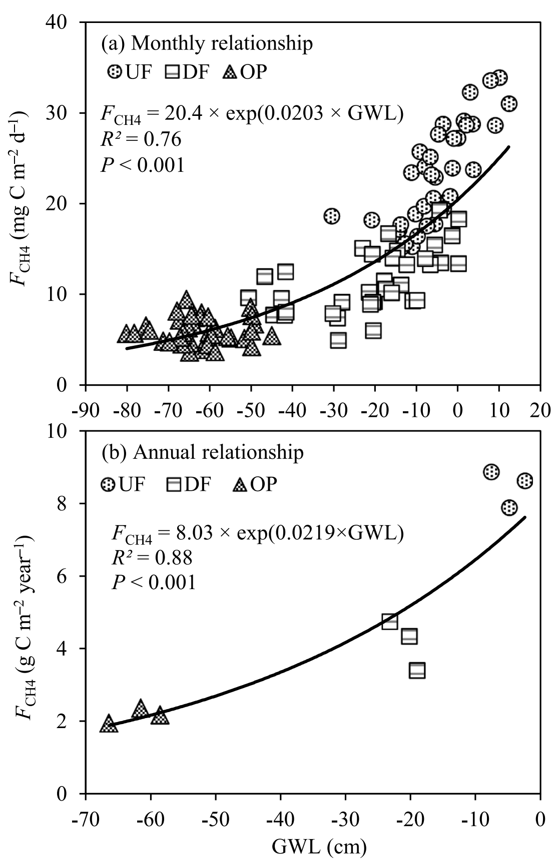


**Fig. 7.** (a) Monthly and (b) annual relationships between gap-filled net ecosystem $CH_4$ exchange ($F_{CH4}$) and groundwater level (GWL) in the undrained peat swamp forest (UF), relatively disturbed secondary peat swamp forest (DF), and oil palm plantation (OP). Exponential curves show the significant relationships.

### 3.6. Comparison with other studies

Soil $CH_4$ fluxes from tropical peat ecosystems have been measured using soil static chambers. Table 5 shows various published findings of annual $CH_4$ emissions from tropical to high-latitude peat ecosystems that were measured using different techniques. Our previous study reported that the annual $F_{CH4}$ of the UF was 7.5–10.8 g C m$^{-2}$ year$^{-1}$ from March 2014 to February 2015 (Wong et al., 2018), which is in accordance with the annual $F_{CH4}$ of the UF in this study (8.46 g C m$^{-2}$ year$^{-1}$). Regarding tropical PSFs, annual soil $CH_4$ emissions (–0.28 to +1.2 g C m$^{-2}$ year$^{-1}$) from chamber and incubation studies (Inubushi et al., 2003; Jauhiainen et al., 2005, 2008; Melling., 2005a; Sangok et al., 2017) were much lower than the $F_{CH4}$ values of the UF and DF in the present study, except for in the study of Hadi et al. (2005) (4.4 g C m$^{-2}$ year$^{-1}$). Although there are large variations among study sites (Table 5), the mean annual $CH_4$ emissions measured by the eddy covariance technique in mid- and high-latitude peat ecosystems were 13 g C m$^{-2}$ year$^{-1}$ on average, with a range of 4.1 to 22.6 g C m$^{-2}$ year$^{-1}$ (Hargreaves et al., 2001; Rinne et al., 2007; Jackowicz-Korczyński et al., 2010; Tagesson et al., 2012; Hanis et al., 2013; Olson et al., 2013; Song et al., 2015; Helbig et al., 2017; Fortuniak et al., 2017). The annual $CH_4$ emission of the UF was much lower than those of temperate peatlands, similar to those of a subarctic oligotrophic fen (Rinne et al., 2007), subarctic boreal forest (Helbig et al., 2017) and Arctic fen (Tagesson et al., 2012), and higher than those of subarctic fens (Hargreaves et al., 2001; Hanis et al., 2013). The annual emission of the DF was almost equivalent to those of subarctic fens (Hargreaves et al., 2001; Hanis et al., 2013). In the UF, $CH_4$ emission was lower than those of temperate peatlands, despite the high temperatures. This relatively lower emission might be due to the combined effect of the poor quality of woody peat with high lignin content and effective $CH_4$ oxidation on the surface layer (Jauhiainen et al., 2016; Wright et al., 2011). Furthermore, an oxygen supply through the plant roots could reduce $CH_4$ production even under flooded conditions (Adji et al., 2014).

One study reported that the annual soil $CH_4$ emission from an oil palm plantation on peat (Melling et al., 2005a) was slightly negative, and that a drained PSF was also a $CH_4$ sink (Jauhiainen et al., 2008). In contrast, the monthly and annual $F_{CH4}$ values were always positive in the OP, and much greater than the annual soil $CH_4$ emissions reported from other PSFs (Jauhiainen et al., 2005; Melling et al., 2005a; Sangok et al., 2017).

The annual $F_{CH4}$ was also reported from an undrained PSF in Central

**Table 5**
Comparison of annual $CH_4$ emissions from peatlands.

| Climate | Location | Technique | Ecosystem | $CH_4$ emission ( g C $m^{-2}$ $year^{-1}$) | Reference |
|---|---|---|---|---|---|
| Tropical | Sarawak, Malaysia | Eddy covariance | UF | 8.46 | This study |
| | | | DF | 4.17 | |
| | | | OP | 2.19 | |
| Tropical | Sarawak, Malaysia | Eddy covariance | UF | 7.5–10.8 | Wong et al. (2018) |
| Tropical | Central Kalimantan, Indonesia | Eddy covariance | Undrained secondary forest | 0.09–0.17 | Sakabe et al. (2018) |
| Tropical | South Kalimantan, Indonesia | Soil static chamber | Secondary forest | 1.2 | Inubushi et al. (2003) |
| Tropical | South Kalimantan, Indonesia | Soil static chamber | Secondary forest | 4.4 | Hadi et al. (2005) |
| Tropical | Sarawak, Malaysia | Soil static chamber | Mixed peat swamp forest | 0.018 | Melling et al. (2005a) |
| | | | Oil palm plantation | –0.015 | |
| Tropical | Central Kalimantan, Indonesia | Soil static chamber | Logged over forest | < 1.02 | Jauhiainen et al. (2005) |
| Tropical | Central Kalimantan, Indonesia | Soil static chamber | Deforested area | 0.148–0.205 | Jauhiainen et al. (2008) |
| | | | Drainage-affected selectively logged forest | –0.28 to –0.16 | |
| Tropical | Sarawak, Malaysia | Field incubation experiment | Peat samples from Mixed peat swamp, Alan Batu and Alan Bunga forests (in an oil palm plantation) | 0.113–0.253 | Sangok et al. (2017) |
| Temperate | Minnesota, USA | Eddy covariance | Poor fen | 16.3[a] | Olson et al. (2013) |
| Temperate | Qinghai plateau, China | Eddy covariance | Alpine peatland (silty clay loam) | 22.6[a] | Song et al. (2015) |
| Temperate | Biebrza, Poland | Eddy covariance | River valley fen | 18.4[a] | Fortuniak et al. (2017) |
| Subarctic | Kaamanen, Finland | Eddy covariance | Aapa mire (fen) | 4.1 | Hargreaves et al. (2001) |
| Subarctic | Ruovesi, Finland | Eddy covariance | Oligotrophic fen | 9.4 | Rinne et al. (2007) |
| Subarctic | Stordalen, Sweden | Eddy covariance | Mosaic of ombrotrophic and minerotrophic peatlands | 20.2[a] | Jackowicz-Korczyński et al. (2010) |
| Subarctic | Manitoba, Canada | Eddy covariance | Eutrophic fen | 5.2[b] | Hanis et al. (2013) |
| Subarctic | Scotty Creek, Canada | Eddy covariance | Boreal forest | 9.7* | Helbig et al. (2017) |
| Artic | Zackenberg, Greenland | Eddy covariance | Fen | 7.1[a] | Tagesson et al. (2012) |

UF, undrained peat swamp forest; DF, relatively disturbed secondary peat swamp forest; OP, oil palm plantation.
[a] Mean of all annual periods.
[b] Mean of all gap-filling methods.
* Snow-free period.

Kalimantan, Indonesia (Sakabe et al., 2018). Although its annual mean GWL (–18 cm) was almost the same as that in DF (–21 cm), the annual $F_{CH4}$ was much lower (0.09–0.17 g C $m^{-2}$ $year^{-1}$) in Central Kalimantan from June 2016 to May 2017 than in the DF (4.17 g C $m^{-2}$ $year^{-1}$). The low $F_{CH4}$ in Central Kalimantan was probably due to drought in the preceding two consecutive El Niño–Southern Oscillation years. In 2014 and 2015, the GWL greatly decreased to –91 and –143 cm, respectively, in the Central Kalimantan site. Oxidative peat decomposition was enhanced during the drought periods; consequently, substrate for $CH_4$ production would have been scarce in the flux measurement period (Sakabe et al., 2018). The results shown in Table 4 partly support this explanation. In addition, peat types in Central Kalimantan and Sarawak are classified as 'inland peat' and 'coastal peat', respectively (Dommain et al., 2011; Kurnianto et al., 2015). Coastal peat is younger than inland peat. The accumulation rate of coastal peat during the Holocene was three times higher than that of inland peats (Dommain et al., 2011), which could lead to a greater $CH_4$ production in coastal peat (Tomassen et al., 2004). Furthermore, significant $CH_4$ production in tropical peatlands has been noted down to depths of 0.48 m by Inubushi et al. (1998), and 0.8 m by Melling et al. (2005a). Considering the deep carbon pool, the $CH_4$ production in the deeper peat layers may be of considerable importance. The peat depth was 10–12.7 m in the UF, DF, and OP, which was much deeper than in other sites previously studied (Inubushi et al., 2003; Melling et al., 2005a; Jauhiainen et al., 2005, 2008; Sakabe et al., 2018).

Recently, a study reported a global synthesis of eddy covariance $CH_4$ flux measurements at 60 sites globally (Knox et al., 2019). According to that study, the median annual $CH_4$ emissions from tundra, boreal/taiga, temperate, and tropical/subtropical wetlands were 2.9, 9.5, 27.4, and 43.2 g C $m^{-2}$ $year^{-1}$, respectively. In this study, the median annual $CH_4$ emissions of UF, DF, and OP were 8.63, 4.35, and 2.23 g C $m^{-2}$ $year^{-1}$, respectively. In comparison with Knox et al. (2019), the median annual $F_{CH4}$ of UF was much higher than the tundra wetlands, similar to the boreal/taiga wetlands, and much lower than the temperate and tropical/subtropical wetlands. The median annual $F_{CH4}$ of DF and OP were much lower than the temperate and tropical/subtropical wetlands.

### 3.7. $CH_4$ sources

The annual $F_{CH4}$ values measured by the eddy covariance technique were much larger than the soil $CH_4$ emissions from tropical peatlands. This difference probably arose from the high heterogeneity of the forest floor and various $CH_4$ fluxes other than in the soil. There is a microtopography consisting of hollows and hummocks on the PSF floor. Some hollows were flooded even in the dry period, especially in the UF. These hollows could be hot spots of $CH_4$ emission, because soil $CH_4$ emissions from hollows are much higher than those from hummocks (Pangala et al., 2013). It is difficult to cover all hot spots using the chamber technique.

Trees adapted to waterlogged soil have developed a morphological structure with root systems penetrating anoxic soil horizons, which can facilitate the egress of soil $CH_4$ (Terazawa et al., 2007; Gauci et al., 2010; Rice et al., 2010; Pangala et al., 2013, 2015, 2017). In the UF and DF, the tree roots penetrated a deeper peat layer (below –20 cm), allowing $CH_4$ to bypass the aerobic layer within the peat profile. In Central Kalimantan, the $CH_4$ emissions from the tree stems were greater than those from the peat surface, accounting for 62%–87% of the total ecosystem $CH_4$ efflux from a relatively undrained tropical PSF (Pangala et al., 2013). A recent study reported that $CH_4$ efflux from tree stems is the dominant source of ecosystem $CH_4$ emissions in Amazon floodplains (Pangala et al., 2017). Moreover, Wang et al. (2016) inferred that $CH_4$ emitted from tree stems in wet soil was partly derived from the $CH_4$ produced in wet heartwood. Emissions via tree stems might be more important during a low GWL period, because $CH_4$ oxidation can be high in the thickened unsaturated peat layer. The stem $CH_4$ efflux would then be the main reason for the higher ecosystem $CH_4$ emissions from the UF and DF.

In drained peatlands, $CH_4$ efflux from the soil surface tends to be near zero or negative (sink) (Roulet et al., 1993; Martikainen et al., 1995; Flessa et al., 1998; Melling et al., 2005a; von Arnold et al., 2005; Jauhiainen et al., 2008; Ojanen et al., 2010). However, it has been reported that ditches within drained sites can serve as important sources of $CH_4$ (Minkkinen and Laine, 2006; Hendriks et al., 2007; Teh et al., 2011; Hyvönen et al., 2013; Turetsky et al., 2014). A large $CH_4$ efflux can occur from a ditch, if $CH_4$-rich water seeps from the surrounding peat into the ditch and is degassed (Turetsky et al., 2014). Teh et al. (2011) reported that though these ditches occupied only 5% of the land area, they accounted for more than 84% of the $CH_4$ emissions from a temperate peatland pasture. In Central Kalimantan, the mean $CH_4$ efflux of 123 mg C $m^{-2}$ $d^{-1}$ was measured from a settled canal (Jauhiainen and Silvennoinen, 2012). In the OP, the areal ratio of ditches within the fetch area (a radius of 500 m) was 2.4%. Although ditches occupy only a small fraction of the oil palm plantation, the positive annual $F_{CH4}$ of 2.19 g C $m^{-2}$ $year^{-1}$ might have been attributed to $CH_4$ emissions from the small collective area of the ditches, which were covered with water.

### 3.8. Net greenhouse gas balance of DF

According to Kiew et al. (2018), the DF was a net $CO_2$ sink of 136 g C $m^{-2}$ $year^{-1}$. The annual $F_{CH4}$ of 4.17 g C $m^{-2}$ $year^{-1}$ (Table 3) was converted to a $CO_2$ equivalent ($CO_{2e}$) of 251 g $CO_{2e}$ $m^{-2}$ $year^{-1}$ (68 g C_$CO_2$ $m^{-2}$ $year^{-1}$) using the SGWP factor of 45. The SGWP is more robust than the global warming potential because the estimation is based on greenhouse gas fluxes that are sustained over the entire period of interest (Neubauer and Megonigal, 2015). A limitation of the global warming potential is that this metric requires the implicit assumption that greenhouse gas fluxes occur as a single pulse and are not sustained over time. The net greenhouse gas balance ($CO_2$ equivalents) was calculated to be –68 g C $m^{-2}$ $year^{-1}$ as the sum of –136 ($CO_2$) and 68 ($CH_4$) g C $m^{-2}$ $year^{-1}$. Consequently, the $CH_4$ emission moderately decreased the $CO_2$ sequestration by 50%.

### 3.9. Effect of land use change on $CH_4$ balance

The net ecosystem $CH_4$ exchange was always positive on both monthly and annual bases in an undrained PSF, a disturbed PSF, and an oil palm plantation in Sarawak, Malaysia. There was a significant difference in annual $CH_4$ emission among the three sites. Here, conversion from undrained PSF to disturbed PSF with logging and lowering the GWL by drainage reduced more than 50% of the ecosystem $CH_4$ emission. Additionally, conversion from undrained PSF to oil palm plantation decreased the ecosystem $CH_4$ emission by about 75%. In comparison, conversion from disturbed PSF to oil palm plantation decreased about 50% of the ecosystem $CH_4$ emission. The decrease in $CH_4$ emissions may be insufficient to compensate for the $CO_2$ emissions due to oxidative peat decomposition (Hirano et al., 2009; Itoh et al., 2017).

## 4. Conclusions

We have measured the ecosystem-scale $CH_4$ flux above the canopy of the undrained peat swamp forest, relatively disturbed peat swamp forest and oil palm plantation on peat using the eddy covariance technique. This is the first study applying the eddy covariance technique for $CH_4$ flux measurement in the oil palm plantation. Following are the five key findings of this study:

- The $F_{CH4}$ of the peat swamp forests were controlled by GWL and independent of GWL in the oil palm plantation.
- All three ecosystems were net sources of $CH_4$ (2.19–8.46 g C $m^{-2}$ $year^{-1}$) to the atmosphere even in drained oil palm plantation.
- Annual $CH_4$ emissions from the peat ecosystems in this study were lower than those from mid-latitude peat ecosystems, though it was much higher than soil $CH_4$ emissions measured by the chamber technique.
- The $CH_4$ emission from the tropical peat swamp forest potentially offset the $CO_2$ sequestration by the ecosystem, in which 50% offset occurred in the relatively disturbed peat swamp forest.
- Conversion of a peat swamp forest to an oil palm plantation decreases $CH_4$ emissions because the land conversion accompanies drainage.

Despite the huge carbon stocks in tropical peatlands, data on ecosystem-scale $CH_4$ fluxes are very limited. The data of this study will contribute to improve the modeling of $CH_4$ fluxes of tropical peatlands, and thus reduce the uncertainty in estimating the $CH_4$ balance of Southeast Asian wetland. In addition, the annual $CH_4$ emissions will provide a basis for $CH_4$ emission factor definition for peatland conversion in Southeast Asia.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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