# Methane balances of tropical peat ecosystems in Sarawak, Malaysia

（マレーシア・サラワク州における熱帯泥炭生態系のメタン収支）

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## 1. Introduction

The atmospheric concentration of methane ($CH_4$) has increased greatly 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, contributing to about one-third of total emissions (Zhang et al., 2017). Zhang et al. (2017) estimated that tropical wetlands remain the world's largest natural source responsible for about 53.2 ± 0.7% of $CH_4$ emissions by the end of the 21st century under representative concentration pathway 8.5 despite decreasing wetland extent and increased drought frequency in tropics. In Southeast Asia, the $CH_4$ emission from the wetlands has been estimated as large as 26 Tg $CH_4$ $yr^{-1}$ (Kirschke et al., 2013).

Tropical peatland is one of the typical wetlands. It is widely distributed in Southeast Asia, with about 20.7 Mha in Indonesia and 2.6 Mha in Malaysia (Page et al., 2011). Tropical peat consists mainly of slightly- or partially-decayed trunks, branches and roots of trees (Melling and Hatano, 2004), and reserves huge carbon in peat soil over millennia (Dommain et al., 2011). Most of the tropical peatlands are located in coastal lowlands with high groundwater level (GWL). Given their large soil carbon stock, high GWL and high tropical temperature, tropical peatlands potentially function as a significant source of $CH_4$ to the atmosphere. Conversion of tropical peat swamp forests (PSF) into monoculture plantations of oil palm or pulpwood has become a global concern (e.g., Melling et al., 2005b; Germer and Sauerborn, 2008; Gaveau et al., 2014; Carlson et al., 2015; Miettinen et al., 2017). Land conversion with drainage of peat swamp forest lowers GWL and increase peat carbon loss due to oxidation (Hirano et al., 2009; Jauhiainen et al., 2012). Also, the drainage thins the anaerobic soil layer which may reduce $CH_4$ emissions (Melling et al., 2005a).

To date, only a few studies have measure soil $CH_4$ flux periodically by the chamber technique from tropical peatlands although there are several types of PSF (Inubushi et al., 2003; Hadi et al., 2005; Jauhiainen et al., 2005; Melling et al., 2005a; Hirano et al., 2009). The soil chamber technique is insufficient to quantify the $CH_4$ emissions from PSF because

$CH_4$ is not only emitted from the soil, but also from tree stems (Pangala et al., 2013). In addition, it is difficult to quantify whole ecosystem flux from periodic chamber measurement with limited spatial replication especially with the heterogeneous microtopography on the forest floor (Dislich et al., 2017). Alternatively, the tower-based micrometeorological approaches, such as the eddy covariance technique, has now been widely used to measure ecosystem-scale $CH_4$ flux over a larger area (~$10^3$–$10^5$ $m^2$) (e.g., Hanis et al., 2013; Nadeau et al., 2013; Song et al., 2015). The eddy covariance technique enables continuous flux measurement with minimal disturbance and allows us to quantify $CH_4$ flux on multiple time scales (Rinne et al., 2007).

To our knowledge, there is still no study reporting the long-term $CH_4$ flux measurements from tropical peat ecosystems. To addresses this knowledge gap, we measured $CH_4$ flux above three different tropical peat ecosystems in Sarawak, Malaysia using the eddy covariance technique for the period from February 2014 to January 2017 (three years). The sites are representing a different degree of disturbance; namely an undrained peat swamp forest (UF), a relatively disturbed secondary peat swamp forest (DF) and an oil palm plantation (OP) on peatland. The objectives of this study were to: (1) quantify the net ecosystem exchange of $CH_4$ ($F_{CH4}$) in each ecosystem, and examine its diurnal and seasonal variations; (2) determine the response of $F_{CH4}$ to GWL; and (3) compare $CH_4$ flux among the three ecosystems and discuss the inter-site difference of $CH_4$ balance.

## 2. Materials and methods

### 2.1 Site description

This study was conducted in three different ecosystems on coastal peat; namely an undrained peat swamp forest (UF; 1°27' N, 111°8' E), a relatively disturbed secondary peat swamp forest (DF; 1°23' N, 111°24' E) and an oil palm plantation (OP; 2°11’ N, 111°50’ E) in Sarawak, Malaysia.

All study sites were located on flat terrains with peat depths of at least 10 m. The UF is part of the Maludam National Park (43,147 ha), and the dominant tree species is *Shorea albida*. In DF, the forest has been selectively logged and regrown as a forest. The surrounding DF has been converted from PSF to oil palm plantations, and consequently the GWL of DF became lower than undisturbed PSF. The dominant tree species are *Litsea spp.* and *Shorea albida*. In OP, a PSF was converted to an oil palm (*Elaeis guineensis* Jacqu.) 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. Ditches and water gates were installed to control GWL.

The climate of the region is equatorial and characterized by consistently high temperature, high humidity and abundant precipitation all year round. Mean annual precipitations (2005–2014) at local meteorological stations near UF, DF and OP were 3201 ± 614, 3358 ± 465 and 2797 ± 224 mm $yr^{-1}$ (mean ± 1 standard deviation (SD)), respectively (Fig. 1). Precipitation is generally higher in December–January in all sites. 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 measurements

Methane flux has been measured above the canopies by the eddy covariance technique since 2012 along with $CO_2$, water vapor and heat fluxes. 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 placed on top of the tower and installed at the tip of a 1-m-long boom projecting towards prevailing wind direction. In UF and DF, the prevailing wind directions are southeast, and in OP is northeast. Sensor signals were sampled at 10 Hz using a datalogger (CR3000, Campbell Scientific Inc.). The system was powered by solar energy.

At each site, solar radiation, air temperature and relative humidity were measured on the tower. Precipitation was measured in a nearby open space. Soil temperature was measured at a depth of 5 cm. Soil moisture was measured in the top 30-cm thick soil. All the meteorological variables above were measured every 10 s and recorded every 5 minutes. GWL was measured by a piezometer and recorded every 30 minutes. A positive GWL represents the water surface to be aboveground, and vice versa.

# 3. Results

## 3.1 Diurnal variations in $CH_4$ fluxes

At all sites, the eddy $CH_4$ flux showed a positive peak in early morning (Fig. 1). In contrast, $CH_4$ storage 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 as a result of increased turbulent mixing after sunrise. The flush out lasted from 07:00 to 11:00. Only UF showed an obvious peak in the early morning with 59 nmol $m^{-2}$ $s^{-1}$ at 08:00. The $CH_4$ storage change was calculated only using $CH_4$ concentration at the top of the tower. Consequently, the $CH_4$ storage change would have been underestimated, especially in UF with a tall forest canopy. The high peak of eddy $CH_4$ flux at UF was not compensated by storage change, because a morning peak appeared in $F_{CH4}$.

## 3.2 Response of $CH_4$ flux to GWL

Influence of GWL on $F_{CH4}$ was examined using regression analysis. To avoid biases due to the morning flush, daily means were used. The daily means of measured $F_{CH4}$ were determined, only if the number of measured data was more than nine on each day. The $F_{CH4}$ showed significant concave quadratic relationship with GWL only at UF ($R^2$ = 0.052; $P$ < 0.001) and DF ($R^2$ = 0.043; $P$ < 0.001).

## 3.3 Seasonal variations in $CH_4$ balance

Monthly values of gap-filled $F_{CH4}$ are shown in Fig. 2. $F_{CH4}$ was always positive in all sites, indicating continuous net $CH_4$ sources to the atmosphere. The range of $F_{CH4}$ variation was largest in UF and smallest in OP. In 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. Monthly $F_{CH4}$ was positively correlated with GWL in UF ($r$ = 0.77; $P$ < 0.001) and DF ($r$ = 0.58; $P$ < 0.001). In OP, however, no significant correlation was found probably because of mechanical compaction and water management. These relationships are compatible with those found using daily means.

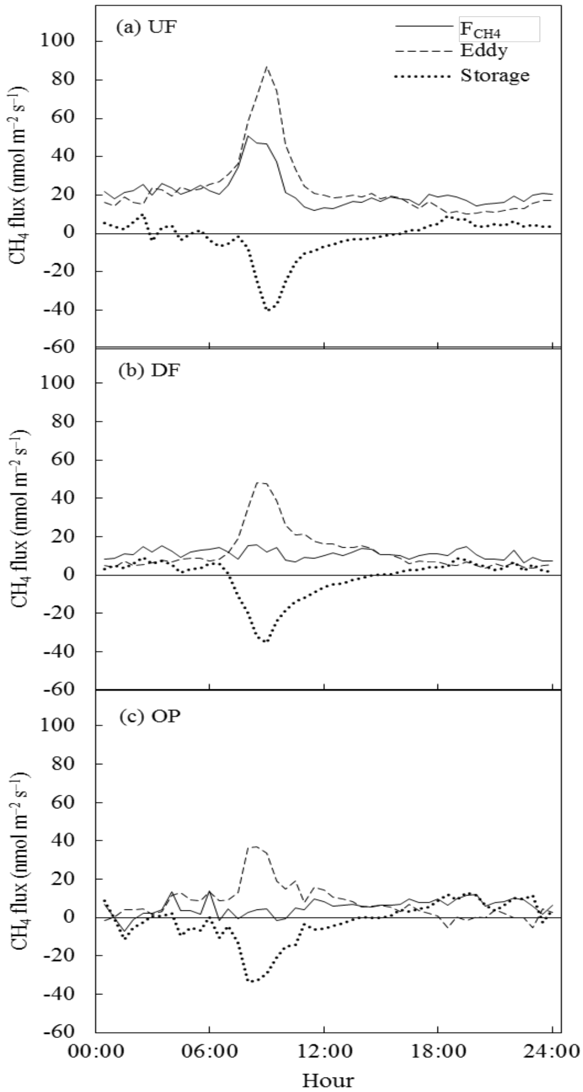


**Fig. 1** Ensemble mean diurnal variations in net ecosystem $CH_4$ exchange ($F_{CH4}$), eddy $CH_4$ flux and $CH_4$ storage change from February 2014 to January 2017 at (a) UF, (b) DF and (c) OP.

## 3.4 Annual $CH_4$ balance

There was significant difference in annual $F_{CH4}$ among the sites ($P$ < 0.001). Mean (± 1 SD) annual $F_{CH4}$ were 8.46 ± 0.51, 4.17 ± 0.69 and 2.19 ± 0.21 g C $m^{-2}$ $yr^{-1}$, respectively, for UF, DF and OP. The mean annual $F_{CH4}$ of UF doubled that of DF and was about four times higher than that of OP. The friction velocity correction was applied only for UF's $F_{CH4}$. To examine the effect of the correction, mean annual $F_{CH4}$ was also calculated without friction velocity correction and resulted in 7.69 ± 0.29 g C $m^{-2}$ $yr^{-1}$, which was smaller than that with friction velocity correction by 0.77 g C $m^{-2}$ $yr^{-1}$ (9%).

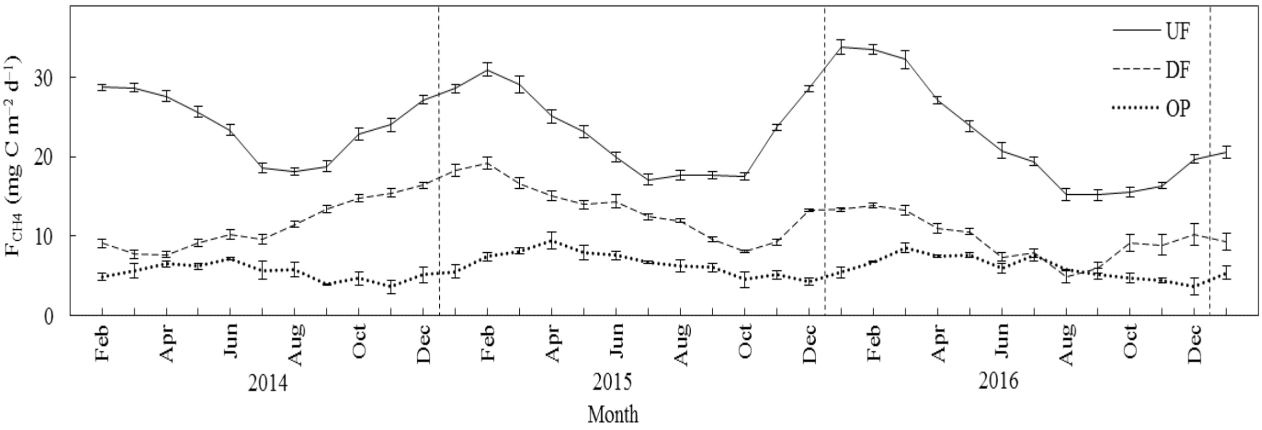


**Fig. 2** Monthly gap-filled daily net ecosystem $CH_4$ exchange ($F_{CH4}$) from February 2014 to January 2017 at UF, DF and OP. Vertical bars denote standard errors.

## 4. Discussion

### 4.1 Comparison of $F_{CH4}$ among three sites

Annual $CH_4$ emission was largest in UF, followed by DF and OP. To examine the difference among sites, gap-filled $F_{CH4}$ was plotted against GWL on monthly and annual bases (Fig. 3), including all data from the three sites. A significant exponential relationship was found both on a monthly ($P < 0.001$; $R^2 = 0.76$) or annual ($P < 0.001$; $R^2 = 0.88$) basis. Monthly mean $F_{CH4}$ increased sharply when monthly mean GWL was above –20 cm, and the relationship suggests that $F_{CH4}$ was more than 20.7 mg C $m^{-2}$ $d^{-1}$ in Sarawak's PSF when the ground is flooded. On an annual basis, annual $F_{CH4}$ might be 8.03 g C $m^{-2}$ $yr^{-1}$, if annual mean with GWL was zero. A similar exponential relationship was reported for annual data of $CH_4$ flux and GWL from northern peatlands

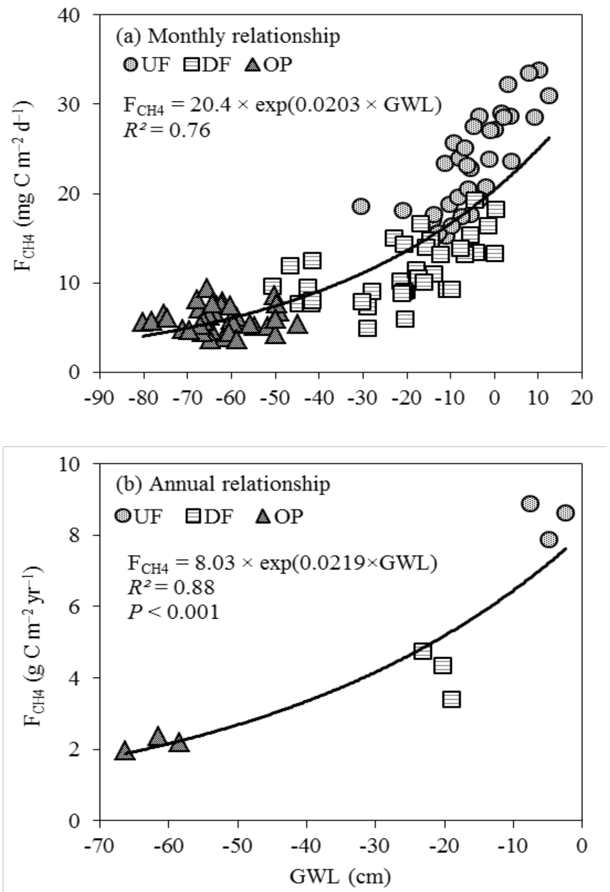


**Fig. 3** Monthly (a) and annual (b) relationships of gap-filled net ecosystem $CH_4$ exchange ($F_{CH4}$) and groundwater level (GWL). An exponential curve was significantly fitted for each relationship.

(Abdalla et al., 2016). The significant relationship indicates that the difference in $F_{CH4}$ among the three sites was mainly due to the difference in GWL. Also, the equations would be applicable to estimate $CH_4$ emissions from peatlands in Sarawak using GWL on a monthly or annual time scale.

### 4.2 Comparison with other studies

Methane fluxes from tropical peat ecosystems have been measured using soil static chambers, except for our previous study (Wong et al., 2018). Our previous study reported that the annual $F_{CH4}$ of UF was 7.5–10.8 g C $m^{-2}$ $yr^{-1}$ from March 2014 to February 2015, which is compatible with this study. In tropical PSF, annual soil $CH_4$ emissions (–0.28 to +1.2 g C $m^{-2}$ $yr^{-1}$) reported by chamber and incubation studies (Inubushi et al., 2003; Jauhiainen et al., 2005, 2008; Melling., 2005a; Sangok et al., 2017) were much lower than $F_{CH4}$ of UF and DF, except for Hadi et al. (2005) (4.4 g C $m^{-2}$ $yr^{-1}$). The annual $CH_4$ emission from UF was much lower than those of temperate peatlands but similar to those of a subarctic oligotrophic fen (Rinne et al., 2007), an arctic fen (Tagesson et al., 2012), and was higher than those of subartic fens (Hargreaves et al., 2001; Hanis et al., 2013). The annual emission of DF was almost equivalent to those of subarctic fens (Hargreaves et al., 2001; Hanis et al., 2013). In UF, $CH_4$ emission was lower than those of temperate peatlands despite high temperature. The relatively lower emission might be due to the combined effect of poor quality of woody peat with much lignin and effective $CH_4$ oxidation in a surface layer (Jauhiainen et al., 2016; Wright et al., 2011). Furthermore, oxygen supply through the plant roots would reduce $CH_4$ production even in flooded conditions (Adji et al., 2014).

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

In Jauhiainen et al. (2008), GWL dropped below –1 m in dry period, which was more than 3.2 times lower than the lowest GWL in UF, 1.9 times in DF and 1.2 times in OP. Higher amount of substrate utilized in the dry period may have led to lower substrate availability in the wet season, which resulted in low $CH_4$ emissions. In addition, the peat types in Central Kalimantan and Sarawak are classified as ‘inland peat’ and ‘coastal peat’, respectively (Dommain et al., 2011; Kurnianto et al., 2015).  The coastal peats are younger than inland peats, with Holocene peat accumulation rate three times higher than the inland peats (Dommain et al., 2011) and may lead to higher $CH_4$ productions (Tomassen et al., 2004). Furthermore, greater $CH_4$ productions in tropical peatlands have been noted down to depths of 0.48 m in Inubushi et al. (1998) and 0.8 m in Melling et al. (2005a). In neotropical peatland, an incubation study recorded potential $CH_4$ fluxes down to a depth of 2 m (Wright et al., 2011). Considering the deep carbon pool, the $CH_4$ production in deeper peat layers may be of considerable importance. The peat depths of UF, DF and OP were 10–12 m, which were more than 1.8 times deeper than in the previous studies on tropical peatlands (Inubushi et al., 2003; Melling et al., 2005a; Jauhiainen et al., 2005; Jauhiainen et al., 2008).

### 4.3 Effect of landuse change on $CH_4$ balance

Net ecosystem $CH_4$ exchange measured by eddy covariance technique was always positive on monthly and annual bases in all the three different tropical ecosystems of 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. From a positive exponential relationship (Fig. 3), the difference was considerably explained by GWL. Here, conversion from undrained PSF to disturbed PSF with logging and lowering GWL by drainage reduced more than 50% of ecosystem $CH_4$ emission. Also, 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 ecosystem $CH_4$ emission. The decrease of $CH_4$ emissions maybe insufficient to compensate the $CO_2$ emissions due to oxidative peat decomposition (Hirano et al., 2009). The oil palm plantation drained deep to –62 cm on average may still functioned as a small $CH_4$ source probably because of high $CH_4$ emissions from ditches.

## 5. Conclusions

The findings of this study can be summarized as follows:

- All ecosystems showed morning flushes of $CH_4$, and an apparent peak in $F_{CH4}$ was observed in UF.
- On a daily basis, the $F_{CH4}$ was positively associated with GWL in UF and DF.
- All ecosystems were net source of $CH_4$ even in the drained ecosystem of oil palm plantation.
- Annual $F_{CH4}$ was significantly different between the ecosystems.

- Overall, the annual $CH_4$ emissions do not exceed those from mid- and high-latitude peatlands, however, the result suggests that tropical peat ecosystems can be one of the important natural $CH_4$ sources in the tropics.