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.

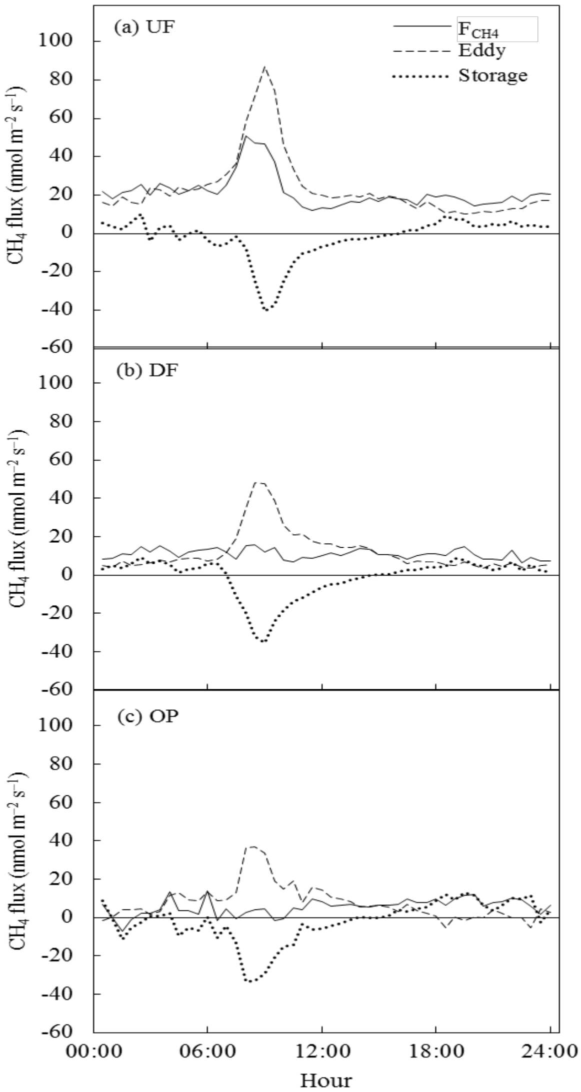

Fig. 1 Ensemble mean diurnal variations in net ecosystem CH_4 exchange (F_{CH4}), eddy CH_4 flux and CH_4 storage change from February 2014 to January 2017 at (a) UF, (b) DF and (c) OP.

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%).

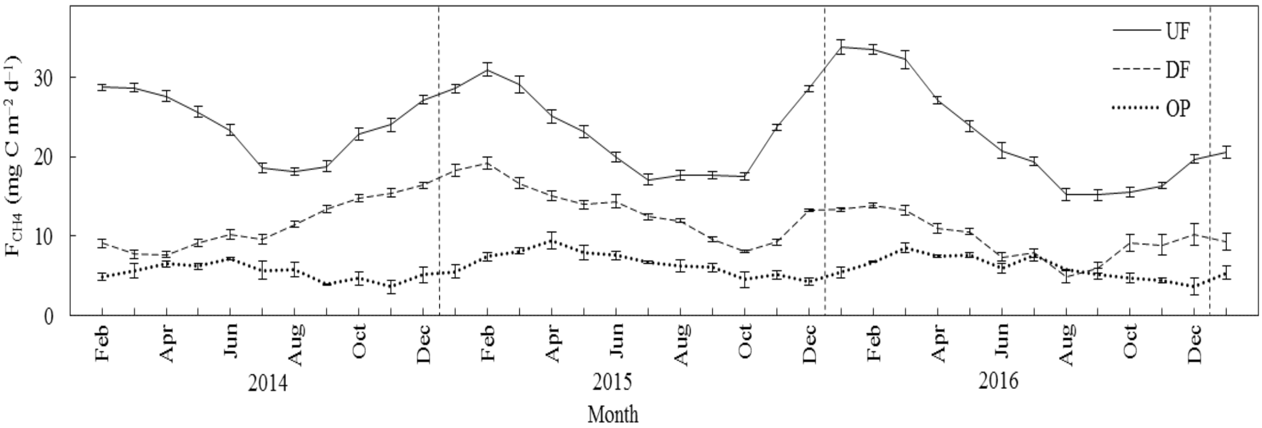

Fig. 2 Monthly gap-filled daily net ecosystem CH_4 exchange (F_{CH4}) from February 2014 to January 2017 at UF, DF and OP. Vertical bars denote standard errors.

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

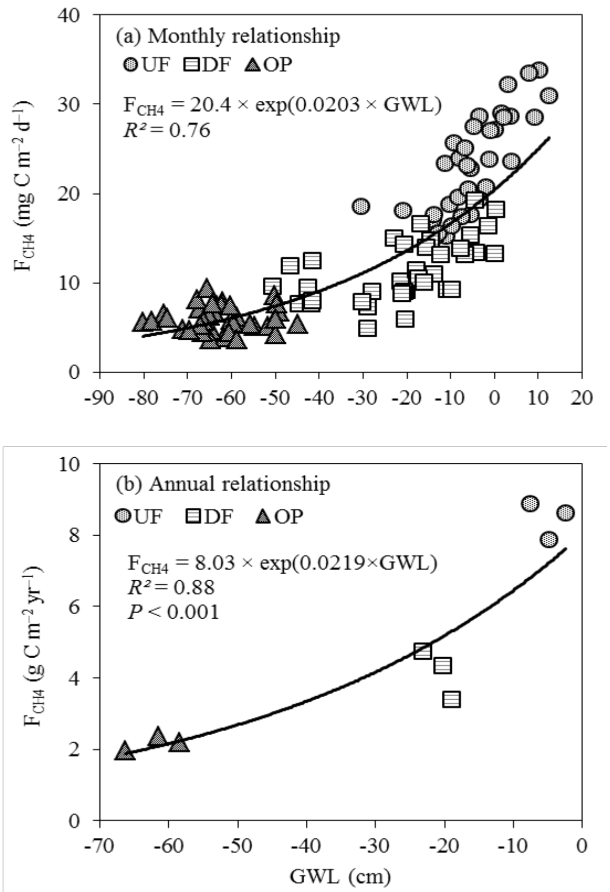

Fig. 3 Monthly (a) and annual (b) relationships of gap-filled net ecosystem CH_4 exchange (F_{CH4}) and groundwater level (GWL). An exponential curve was significantly fitted for each relationship.

(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.