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Micrometeorological measurement of methane flux above a tropical peat swamp forest

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ABSTRACT

Tropical peat swamp forest is a unique ecosystem, in which both swamp forest and peat soil have coexisted over millennia and accumulated a significant amount of soil carbon as peat. Owing to the huge soil carbon stock and high groundwater level (GWL), tropical peatlands potentially represent a significant source of methane (CH_4) to the atmosphere. However, a few studies of CH_4 flux by the soil chamber technique have reported that annual CH_4 emissions from tropical peat swamp forest were very low as compared to mid- and high-latitude peatlands. Recently, it has been reported that some tree species growing in peat swamp forest emit CH_4 from their stems. It is impossible to continuously measure ecosystem-scale CH_4 flux including both soil and plant-mediated CH_4 emissions by the chamber technique. Thus, we have measured net ecosystem CH_4 exchange (FCH_4) above a tropical peat swamp forest in Sarawak, Malaysia using the eddy covariance technique from February 2014 to July 2015 (18 months). The mean (± 1 standard deviation) of half-hourly measured FCH_4 was $24.0 \pm 42.2\,\mathrm{nmol\,m^{-2}\,s^{-1}}$. Monthly mean FCH_4 was always positive during the 18 months, even in the driest month with mean GWL of –30 cm. FCH_4 was positively associated with GWL or soil moisture in a quadratic form. Annual FCH_4 from March 2014 through February 2015 was 7.5–10.8 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$. The annual FCH_4 was much higher than annual soil CH_4 emissions from tropical peatlands, because the FCH_4 included aboveground CH_4 emissions mainly from tree stems. However, the annual FCH_4 was relatively low in comparison with those measured by the eddy covariance technique in mid- and high-latitude peatlands.

1. Introduction

Peatlands constitute about 3% of the global land area, yet they represent the largest long-term carbon pool in the terrestrial biosphere (Maltby and Immirzi, 1993; Yu et al., 2014). In the tropics, large areas of peatland exist in the coastal lowlands of Southeast Asia, with about 20.7 Mha in Indonesia and 2.6 Mha in Malaysia (Page et al., 2011). Recently, a large peatland area of about 14.6 Mha was found in the Congo Basin (Dargie et al., 2017). Both peat swamp forest vegetation and underlying peat have coexisted over millennia and formed a highly-concentrated carbon store (Dommain et al., 2011). Owing to the huge carbon stock in the soils and high groundwater level (GWL), tropical peatlands could be a significant source of methane (CH_4).

Tropical peatlands generally have a dome-shaped surface with greater peat depth towards the centre of the peatland (Melling and Hatano, 2004). Tropical peat mainly originates from slightly- or partially-decayed trunks, branches and roots of trees (Melling and Hatano, 2004). Different species composition and vegetation structures can be seen in different zones of peat domes in Borneo (Anderson, 1961). In Sarawak, Malaysia, six zonal communities of forest vegetation are distributed from the edge to the center of a peat dome (Anderson, 1961). These zonal communities are called as follows: mixed peat swamp, Alan Batu, Alan Bunga, Padang Alan, Padang Selunsor and Padang Keruntum forests from the edge (Anderson, 1961; Phillips, 1998). This sequence is different from that of tropical peat swamp forest in Central Kalimantan, Indonesia (Page et al., 1999). The peat depth, hydrology, decomposition level, soil pH and vegetation composition are different among the zonal communities. Thus, carbon dynamics could be heterogeneous according to the zonal communities.

CH_4 is the second most important greenhouse gas (GHG), with a global warming potential 28 times greater than carbon dioxide (CO_2) over a century (Milich, 1999; IPCC, 2013). The atmospheric concentration of CH_4 has increased by 150% since the pre-industrial era, rising from 722 ppb in 1750 to 1803 ppb in 2011 (IPCC, 2013). The

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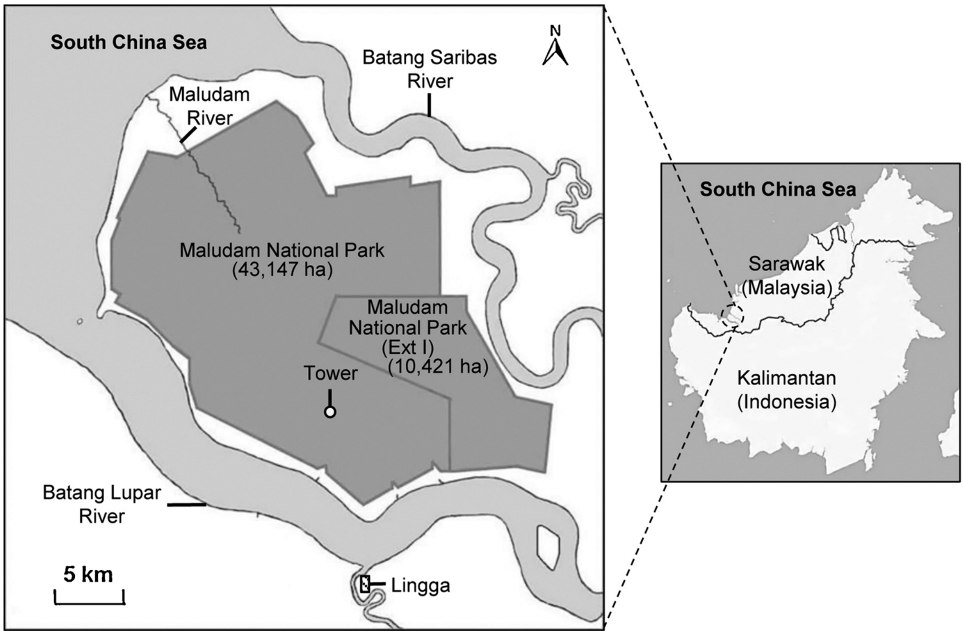

Fig. 1. Map of the study area.

growth rate of CH_4 has declined to near zero during 1999–2006 and increased again in 2007 with two anomalous annual CH_4 emissions estimated by inversions for 2007–2008 (Bousquet et al., 2011; IPCC, 2013). Tropical CH_4 emissions were found to be the main contributor of these emission anomalies (Bousquet et al., 2011). To date, however, there is no evidence that tropical peatland is attributable to the large emissions; this can partly be attributed to a lack of observational data from peat swamp forests. In tropical peat swamp forest, CH_4 flux showed a large spatial variation in horizontal and vertical directions. Microtopography on the forest floor consisting of hummocks and hollows causes the horizontal variation, because soil CH_4 efflux is higher on hollows (Pangala et al., 2013). Also, Pangala et al. (2013) reported that dominant trees in tropical peat swamp forest in Indonesia emitted a considerable amount of CH_4 from their stems. Furthermore, there are CH_4-emitting termites nesting above the ground of tropical peat swamp forests (Fraser et al., 1986; Martius et al., 1993; Jeeva et al., 1999; Vaessen et al., 2011). Thus, the CH_4 is not emitted only from the soil surface but also from tree stems and termites, which causes a vertical variation in CH_4 flux.

Measurement of CH_4 emissions to the atmosphere has largely relied on the static chamber technique and the eddy covariance technique (McDermitt et al., 2011). The chamber technique provides advantages, such as portability, low-cost and detectability of small-scale CH_4 ebullition events in a small sampling area (Nadeau et al., 2013). However, the method is very labour intensive, and is subject to uncertainties due to soil disturbance and insufficient gas mixing (Christiansen et al., 2011). In addition, the chamber technique usually excludes trees. Alternatively, the tower-based micrometeorological approaches, such as the eddy covariance technique, has now been widely used to measure ecosystem-scale CH4 flux over a larger area ($\sim 10^3$–$10^5\,m^2$) (e.g. 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). In middle- and high-latitude peat ecosystems, many studies on CH_4 flux have been conducted by the eddy covariance technique (e.g. Rinne et al., 2007; Jackowicz- Korczyński et al., 2010; Nadeau et al., 2013; Olson et al., 2013; Song et al., 2015). In tropical peat swamp forest, however, there are only a few soil chamber studies (Melling et al., 2005; Jauhiainen et al., 2005, 2008; Hirano et al., 2009), which reported that CH_4 emissions from tropical peat were lower than those of boreal Sphagnum-dominated bogs.

To our knowledge, there is still no study reporting the CH_4 balance of tropical peat swamp forest using the eddy covariance technique. It is essential to quantify the CH_4 balance of tropical peat swamp forest from field measurement to know its contribution to the tropical CH_4 budget. Therefore, we have measured CH_4 flux above a tropical peat swamp forest using the eddy covariance technique during the period from February 2014 to July 2015 (18 months). The objectives of this study were to: (1) quantify the net ecosystem exchange of CH_4 (FCH_4); (2) examine both the diurnal and seasonal variations of FCH_4; and (3) determine the environmental factors that influence the FCH_4. The outcomes from this study will contribute to a better assessment of FCH_4 for tropical peat swamp forest.

2. Material and methods

2.1. Site description

The study was conducted in Maludam National Park, about 45 km northwest from Betong Division of Sarawak, Malaysia. Maludam National Park is a tropical peat swamp forest located in Maludam Peninsula and covers an area of 43,147 ha (Fig. 1). The Maludam Peninsula is bordered by the Batang Lupar and Batang Saribas Rivers, which flow into the South China Sea. The national park had been subjected to selective logging before it was gazetted as a totally protected area in 2000 (Chai, 2005). Currently, it remains as the largest peat swamp forest in Sarawak. In 2015, the national park was expanded by taking the neighbouring area (Ext I) covering another 10,421 ha. There are four zonal communities in the national park, namely Mixed peat swamp, Alan Batu, Alan Bunga and Padang Alan forests with different tree compositions, heights, densities and peat types (Anderson, 1961; Melling, 2016). In 2010, a 40 m tower was established in the southern part of the national park (1° 27′ 12.87″ N, 111° 8′ 58.17″ E) to measure eddy flux and environmental variables. The tower is located in an ombrotrophic Alan Batu forest, about 4.5 km away from the Batang Lupar River. Alan Batu forest is characterized by its extensive root system which commonly creates a vacant zone of 20–30 cm thickness within the top 100 cm of the peat profile (Melling, 2016).

Around the tower, the terrain is generally flat with an elevation of about 8–9 m above mean sea level with an average peat depth of 10 m. The forest structure is mixed, and the canopy is uneven with a height of 30–35 m. Most of the tree diameters at breast height (DBH, 1.3 m) were in the range of 10–20 cm. Tree density with DBH larger than 5 cm was 1173 trees ha^{-1}. Fetches are longer than 4 km in all directions, which stretches over Mixed Peat Swamp and Alan Bunga forests. Plant area index has been measured monthly since 2013 using a plant canopy analyser (LAI-2200, Li-Cor Inc., Lincoln, NE, USA) at 20 points at 1.3 m height around the tower. Mean plant area index was 6.4 $m^2\,m^{-2}$ and showed no distinct seasonal variation. The forest floor is uneven with hummock-hollow microtopography and covered with thick root mats and tree debris, mostly leaf litter. Hummocks are mainly overgrown with dense tree roots. Hollow surfaces are generally 30–40 cm lower than hummock tops. Dominant tree species in the Alan Batu forest are *Shorea albida*, *Lithocarpus sp.*, *Litsea sp.* and *Dillenia sp.*, and the forest floor is dominated by their young trees, rich shrubs, pitcher plants and pandanus.

The climate at the study site is equatorial, which is characterized by consistently high temperature, high humidity, and abundant precipitation throughout a year. Mean annual precipitation for 17 years (1998–2014) was 3182 ± 494 mm (mean ± 1 standard deviation (SD)), measured at Lingga rainfall station about 12 km away from the study site. Mean annual air temperature in the same period (1998–2014) was 26.5 ± 0.2 °C at Kuching International Airport, about 90 km away from the study site. Precipitation is generally lower in July-August and higher in December-January. GWL is typically high and rises aboveground during the wettest period. The soil pH and carbon: nitrogen ratio (C/N) at 0–50 cm depth were 3.4 and 32.2, respectively

2.2. Measurement of CH_4 flux and environmental variables

CH_4 flux measurement by the eddy covariance technique started in September 2012. The CH_4 flux was measured using an open-path CH_4 analyser (LI-7700, Li-Cor Inc., Lincoln, NE, USA). Three-dimensional wind speeds and virtual temperature were measured using a 3D sonic anemometer/thermometer (CSAT3, Campbell Scientific Inc., Logan, UT, USA). CO_2 and water vapor densities were measured using an open-path CO_2/H_2O analyser (LI-7500A, Li-Cor Inc.). These sensors were placed at the height of 41 m and installed at the tip of a 1-m-long boom projecting towards southeast, which is the prevailing wind direction. The distance between the sonic anemometer/thermometer and the CO_2/H_2O analyser or the CH_4 analyser was 0.1 or 0.6 m, respectively. Signals of the sensors were sampled at 10 Hz using a datalogger (CR3000, Campbell Scientific Inc.). The automated window cleaning of the CH_4 analyser was insufficient to maintain good signal strength. Thus, the upper and lower windows of the CH_4 analyser were manually cleaned twice a month using rain repellent (Rain-X) and tissue paper (Kimwipe). After the manual cleaning, relative signal strength indicator (RSSI) increased up to at least 70%, typically 79%.

Downward and upward shortwave and longwave radiation components were measured at 41 m height using a radiometer (CNR4, Kipp and Zonen, Delft, the Netherlands). Downward and upward photosynthetically active radiation (PAR) components were measured at 41 m height using quantum sensors (LI-190S, Li-Cor Inc.). Air temperature and relative humidity were measured at 3 and 41 m using temperature and relative humidity probes (CS215, Campbell Scientific Inc.) installed in a 6-plate solar radiation shield (41303-5A, Campbell Scientific Inc.). Soil temperature was measured at a depth of 5 cm using a platinum resistance thermometer (C-PTWP, Climatec, Tokyo, Japan). Wind speed and wind direction were measured at 41 m height using a 3-cup anemometer and wind vane (01003-5, R.M. Young Co., Traverse City, MI, USA). Volumetric soil water content was measured in the top 30 cm-thick layer at a hollow using a time domain reflectometry (TDR) sensor (CS616, Campbell Scientific Inc.). Precipitation was measured at 1 m above the ground using a tipping-bucket rain gauge (TE525, Campbell Scientific Inc.) at a nearby open space. All the environmental variables were measured every 10 s and recorded every 5 min with a datalogger (CR1000, Campbell Scientific Inc.). The entire system was powered by solar energy. GWL, which was the distance from a hollow surface, was recorded half-hourly using a GWL logger 181 (HOBO, Onset, Bourne, MA, USA) at a hollow about 20 m away from the tower. Positive and negative values represent GWL above or below the ground, respectively.

2.3. Data processing

Half-hourly mean CH_4 flux was calculated from raw data using Flux Calculator software (Ueyama et al., 2012). The data processing procedures are as follows: (1) despiking (Ueyama et al., 2012), (2) double rotation for tilt correction (Wilczak et al., 2001), (3) block averaging and (4) high frequency loss corrections for path-averaging and sensor separation (Massman, 2000, 2001). The CH_4 flux was corrected for air density fluctuation and spectroscopic effect (Li-Cor Inc., 2010; McDermitt et al., 2011), respectively. FCH_4 was calculated as the sum of eddy CH_4 flux and change in CH_4 storage in an air column below the flux measurement height. The CH_4 storage change was calculated from CH_4 concentration measured with the open-path analyser for eddy flux measurement above the canopy. In fact, the CH_4 storage change should be calculated using CH_4 profile data to accurately determine FCH_4. However, to measure CH_4 profile, another CH_4 analyser is necessary, resulting in a higher cost and large power consumption. This was unavailable at our site which was powered by solar panels. The one point storage flux would cause a bias in half-hourly flux estimates. In theory, nighttime CH_4 storage was compensated by morning flush, and the bias on daily, monthly and annual sums of FCH_4 would be negligible. This is because the accumulated CH_4 below the canopy during nighttime would be released as soon as the onset of turbulence after sunrise. The flux capture by the eddy covariance system would simply be delayed. About 3% (two weeks) of data were lost owing to power failure in March 2015. We used the CH_4 flux data from February 2014 to July 2015 for analyses, but to avoid the data gaps due to power failure, the annual FCH_4 was calculated from March 2014 to February 2015.

A series of quality control procedures were used to filter out low-quality FCH_4 data. Firstly, flux data during rain events were excluded. If RSSI was less than 20% owing to dew condensation, rain, dirty windows, etc., flux data were discarded from analysis. To avoid flow distortion by the tower, flux data were removed when wind direction was between 237° and 344° from the north. Then, the flux data was quality-controlled according to the stationary and integral turbulence tests (Foken and Wichura, 1996), high moment test (Vickers and Mahrt, 1997; Mano et al., 2007) and median absolute deviation around the median (Papale et al., 2006). In addition, underestimated flux was screened out using a friction velocity (u^*) threshold. Fig. 2 shows the relationship of CH_4 fluxes with u^* for entire days. FCH_4 and eddy CH_4 flux increased with u^* until 0.17 $m\,s^{-1}$, whereas storage flux remained

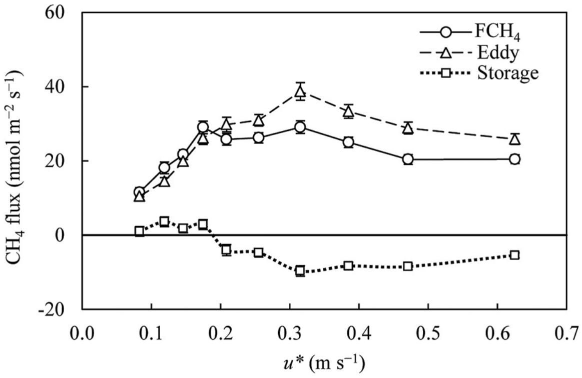

Fig. 2. Relationship of CH_4 fluxes [net ecosystem CH_4 exchange (FCH_4), eddy CH_4 flux and CH_4 storage change] with friction velocity (u^*) for entire days. Half-hourly data were sorted into deciles by u^*. Vertical bars represent 1 standard error.

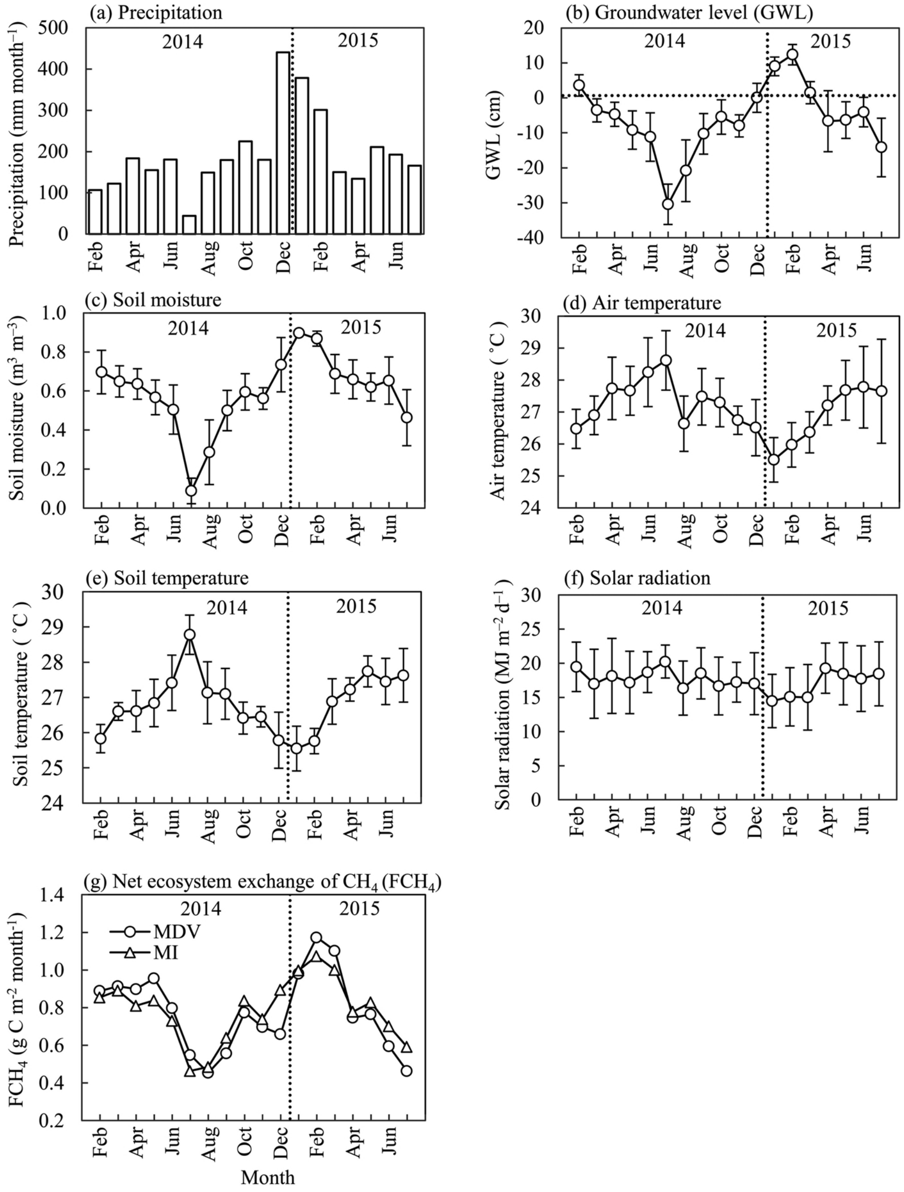

Fig. 3. Seasonal variations in monthly values of (a) precipitation (b) groundwater level (GWL), (c) soil moisture, (d) air temperature, (e) soil temperature, (f) daily solar radiation and (g) gap-filled net ecosystem exchange of CH_4 (FCH_4) including morning flush, from February 2014 to July 2015. Vertical bars represent 1 standard deviation.

slightly positive in the u^* range, and then became negative. According to the procedure described by Saleska et al. (2003) and Hirano et al. (2007), the u^* threshold for FCH_4 was determined at $0.104\,\mathrm{m\,s^{-1}}$ (Tukey's HSD, $P < 0.05$). Eventually, 28% of FCH_4 data survived after the quality control.

Mean diurnal variation (MDV) method (Falge et al., 2001a) was used to gap-fill FCH_4 (Dengel et al., 2011; Jha et al., 2014). Usually, a moving window of 7–14 days is considered appropriate. In this study, because a large amount of data was rejected through the quality control, a longer interval of ± 25 days was used. In addition, we also gap-filled FCH_4 using the multiple imputation method, which imputes missing values with multiplesets of simulated values. Hui et al. (2004) reported that the multiple imputation by Markov Chain Monte Carlo (MCMC) algorithm was comparable to other gap-filling methods (Falge et al., 2001a, b). However, the MCMC algorithm requires the assumption of multivariate normality (Schafer, 1997). In our study, no multivariate normal distribution was found for FCH_4 and environmental variables (Mardia's test, $P < 0.05$). An alternative to MCMC algorithm is the multivariate imputation by chained equations (MICE) algorithm without requirement for multivariate normal distribution (van Buuren and Groothuis-Oudshoorn, 2011). We applied the multiple imputation (MI) by MICE algorithm for gap-filling FCH_4 by implementing MICE package in the R statistical software (R Core Team, 2017). Environmental variables used in the MI method were GWL and soil moisture. To assess the performance of MI for the gap filling of FCH_4, the bootstrap method was applied. Artificial gaps were given randomly at the actual missing rate (72%) to the surviving data set ($n = 7404$) from February 2014 to July 2015. As a result of 100-times run, the mean values (± 1 SD, $n = 5312$) of mean measured FCH_4 (before giving artificial gaps) and mean gap-filled FCH_4 were 23.95 ± 0.29 and $23.97 \pm 1.10\,\mathrm{nmol\,m^{-2}\,s^{-1}}$, respectively. Although the standard deviation was larger in gap filling, MI showed a good performance to estimate mean FCH_4 with many data gaps.

Table 1
Annual means of environmental variables from March 2014 to February 2015.

Environmental variable	Annual mean
Precipitation (mm)	2540
GWL (cm)	–23
Soil moisture ($m^3\,m^{-3}$)	0.57
Air temperature (°C)	27.1
Soil temperature (°C)	27.0
Daily solar radiation ($MJ\,m^{-2}\,d^{-1}$)	17.2

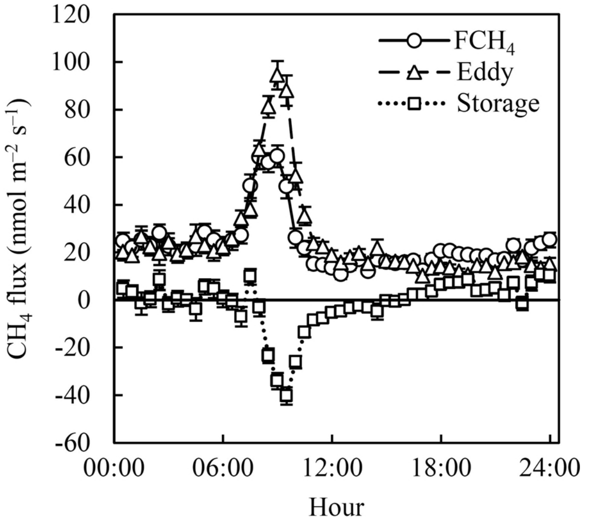

Fig. 4. Ensemble-averaged diurnal variation in measured eddy flux, storage change and net ecosystem exchange of CH_4 (FCH_4) from February 2014 to July 2015. Vertical bars represent 1 standard error.

3. Results

3.1. Seasonal variations in environmental variables

The monthly precipitation at the study site decreased from January to July, and then increased from August to December in three years from 2011 to 2013 (data not shown). This seasonal pattern is similar to the 17-year-long record (1998 to 2014) at Lingga rainfall station (data not shown). On the contrary, seasonal variation was anomalous in 2014 (Fig. 3a). Monthly precipitation was relatively constant between February and November 2014, except for July with the lowest value of 44 mm $month^{-1}$. Then in December, precipitation suddenly increased up to 441 mm $month^{-1}$. In 2015, monthly precipitation decreased from January to March. Based on monthly precipitation threshold of 100 mm (Malhi et al., 2002), only July 2014 was classified as the dry season. Mean monthly precipitation from December 2014 to February 2015 was eight times higher than that in July 2014.

Seasonal variation in monthly mean GWL was similar to that in precipitation (Fig. 3b). GWL decreased gradually from 3.6 cm in February 2014 and was lowest at –30 cm in July 2014, and then GWL increased to about 12 cm in February 2015 and decreased again towards July 2015. During a normal year, GWL generally remains near or above the ground surface. However, the lower precipitation in July 2014 lowered monthly mean GWL to –30 cm.

Seasonal variation in soil moisture of the top 30 cm-thick layer was similar to that in GWL; the minimum was 0.09 $m^3\,m^{-3}$ in July 2014 and the maximum was 0.90 $m^3\,m^{-3}$ in January 2015 (Fig. 3c). In contrast, monthly mean air and soil temperatures showed a small peak in July (Fig. 3d and e), whereas their annual ranges were narrow within 3.5 °C. With more precipitation, monthly solar radiation tended to decrease from December to February (Fig. 3f).

Table 1 shows the annual means of environmental variables calculated from March 2014 to February 2015, the same period as for annual FCH_4 calculation. Annual precipitation was 2540 mm, which was 12% less than mean annual precipitation of 2872 ± 571 mm (± 1 SD) from March 2011 to February 2014.

3.2. Diurnal variations in CH_4 fluxes

Both FCH_4 and eddy CH_4 flux were always positive and showed a marked peak early in the morning at around 08:30–09:00 (Fig. 4). The peaks of FCH_4 and eddy CH_4 flux were about 60 and 94 $nmol\,m^{-2}\,s^{-1}$, respectively. The early morning peak was due to the flush out of stored CH_4 in the forest during the nighttime, because turbulent mixing was enhanced after sunrise. Increased CH_4 emissions by the flush lasted from 07:00 to 10:30. CH_4 storage change would have been underestimated, because it was calculated only using CH_4 concentrations at the top of the tower. Thus, the high peak of eddy flux was not compensated by storage change, and consequently the apparent morning peak appeared even in FCH_4. This fact suggests that nighttime FCH_4 was underestimated.

3.3. Seasonal variation in CH_4 flux

Mean half-hourly measured FCH_4 (± 1 SD) from February 2014 to July 2015 was 24.0 ± 42.2 $nmol\,m^{-2}\,s^{-1}$, indicating that this ecosystem was a net CH_4 source to the atmosphere. On a monthly basis, gap-filled FCH_4 by the MDV and MI methods were always positive (Fig. 3g). Seasonal variation in gap-filled FCH_4 was almost similar with GWL or soil moisture (Fig. 3b and c). FCH_4 remained relatively constant from February to May 2015, decreased in July or August 2015, increased to February 2015, and then decreased towards July 2015. Monthly FCH_4 ranged from 0.45 to 0.46 $g\,C\,m^{-2}\,month^{-1}$ in July or August 2014 to

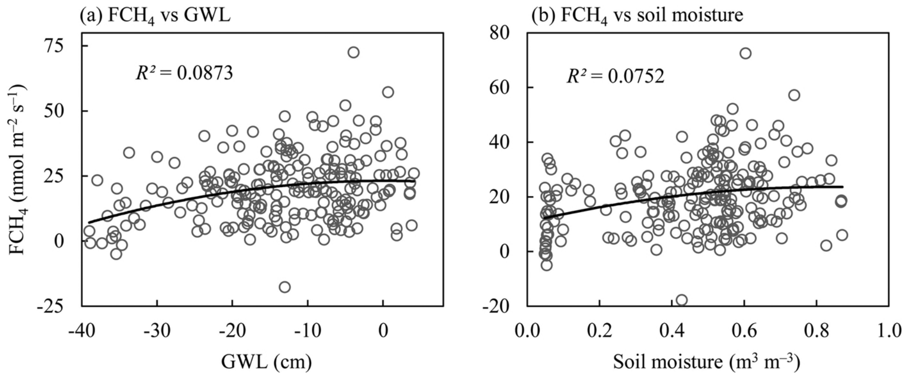

Fig. 5. Relationship of daily mean net ecosystem CH_4 exchange (FCH_4) with (a) groundwater level (GWL) or (b) soil moisture of the top 30 cm-thick layer. A significant quadratic curve is drawn in each panel.

Table 2

Annual FCH_4 calculated from March 2014 to February 2015 under different conditions.

CH_4 flux	Morning flush	Gap filling	Surviving rate (%)	Mean ± 1 SD ($nmol\,m^{-2}\,s^{-1}$)	Annual FCH_4 ($g\,C\,m^{-2}\,yr^{-1}$)
Eddy + storage	With	MDV	27	24.8 ± 25.3	9.4
		MI	27	25.7 ± 42.6	9.7
	Without	MI	21	21.2 ± 34.8	8
Eddy	With	MDV	27	25.8 ± 29.7	9.8
		MI	27	28.5 ± 47.5	10.8
	Without	MI	21	19.8 ± 30.8	7.5

Table 3

Comparison of annual CH_4 emissions with previous studies.

Climate	Location	Ecosystem	Technique	Air temperature (°C)	CH_4 emission ($g\,C\,m^{-2}\,yr^{-1}$)	References
Tropical	Sarawak, Malaysia	Alan Batu forest	Eddy covariance	27.1	7.5–10.8	This study
Tropical	Sarawak, Malaysia	Mixed peat swamp forest	Chamber	27.4	0.018	Melling et al. (2005)
Tropical	Central Kalimantan, Indonesia	Logged over peat swamp forest	Chamber	26.4	< 1.02	Jauhiainen et al. (2005)
Tropical	Central Kalimantan, Indonesia	Deforested area	Chamber	24–27	0.148–0.205	Jauhiainen et al. (2008)
Tropical	Sarawak, Malaysia	Peat samples from Mixed peat swamp, Alan Batu and Alan Bunga forests (in an oil palm plantation)	Field incubation experiment	–	0.113–0.253	Sangok et al. (2017)
Temperate	Minnesota, USA	Poor fen	Eddy covariance	4.4	11.8–24.9	Olson et al. (2013)
Temperate	Qinghai plateau, China	Alpine peatland (silty clay loam)	Eddy covariance	–1.2	19.8–25.3	Song et al. (2015)
Subarctic	Kaamanen, Finland	Oligotrophic fen	Eddy covariance	–	4.1	Hargreaves et al. (2001)
Subarctic	Ruovesi, Finland	Large patterned fen	Eddy covariance	3.3	9.4	Rinne et al. (2007)
Subarctic	Stordalen, Sweden	Mosaic of ombrotrophic and minerotrophic peatlands	Eddy covariance	–0.2	18.3–22.1	Jackowicz- Korczyński et al. (2010)
Subarctic	Manitoba, Canada	Eutrophic fen	Eddy covariance	–	4.9–5.3	Hanis et al. (2013)
Arctic	Zackenberg, Greenland	Fen	Eddy covariance	–9.0	6.5–7.6	Tagesson et al. (2012)

1.07–1.17 $g\,C\,m^{-2}\,month^{-1}$ in February 2015. Mean monthly FCH_4 gap-filled by the MDV and MI methods were 0.78 and 0.79 $g\,C\,m^{-2}\,month^{-1}$, respectively.

3.4. Responses of CH_4 flux to environmental variables

Influence of GWL, soil moisture or soil temperature on FCH_4 were examined using linear or curvilinear regression. To avoid biases due to the morning flush, daily means were used. The daily means of measured FCH_4 were determined, only if the number of measured data was more than nine on each day. The relationship of the FCH_4 with GWL or soil moisture was best-fitted with a concave quadratic curve, respectively ($P < 0.001$) with a peak of 23 $nmol\,m^{-2}\,s^{-1}$ at GWL of 0 cm or soil moisture of 0.84 $m^3\,m^{-3}$ (Fig. 5). The FCH_4 was negatively correlated with soil temperature ($P < 0.001$, data not shown), but the relationship was probably due to a negative correlation between soil temperature and GWL ($r = -0.78$, $P < 0.001$).

3.5. Annual FCH_4

To evaluate uncertainties, annual FCH_4 from March 2014 to February 2015 were estimated under different conditions (Table 2), which shows the effect of morning flush and gap-filling methods on annual FCH_4. The annual FCH_4 ranged from 7.5 to 10.8 $g\,C\,m^{-2}\,yr^{-1}$, with an average of 9.2 $g\,C\,m^{-2}\,yr^{-1}$. Mean annual FCH_4 with and without morning flushes were 9.6 and 8.0 (from eddy plus storage fluxes), respectively, and 10.3 and 7.5 $g\,C\,m^{-2}\,yr^{-1}$ (from eddy flux), respectively. Obviously, excluding morning flushes resulted in less annual emissions. As for gap-filling methods, annual emissions were smaller by the MDV than MI methods by 0.3 (from eddy plus storage fluxes) and 1.0 $g\,C\,m^{-2}\,yr^{-1}$ (from eddy flux). Because the storage flux was measured at only one point above the canopy and the accumulated nighttime CH_4 was compensated by morning flush, the most reliable annual FCH_4 could be estimated using eddy flux data with morning flushes. The annual FCH_4 estimated under this condition were 9.8 and 10.8 $g\,C\,m^{-2}\,yr^{-1}$, respectively, by the MDV and MI methods.

4. Discussion

4.1. Environmental control on CH_4 flux

In this study, GWL was relatively high and never dropped below –30 cm even in the driest month of July 2014, when monthly precipitation was only 44 mm. As shown in Fig. 5a, FCH_4 showed a significant concave quadratic relationship with GWL and peaked at GWL of 0 cm, just at the hollow surface. The relationship shows that the FCH_4 values were more scattered during higher GWL. The scattered FCH_4 may be attributable to the patchy distribution of flooding spots on the ground during higher GWL conditions. The patchy distribution of CH_4 sources leads to different eddy-flux footprints depending on wind direction and atmospheric stability, which probably caused the scattered FCH_4. Soil moisture was regulated by GWL ($r = 0.97$, $P < 0.001$), and these water-related factors are very important in controlling CH_4 emissions from tropical peat swamp forest. High GWL leads to oxygen depletion and inhibits CH_4 oxidation and promotes methanogenesis in the soil (Grünfeld and Brix, 1999). Similarly, high soil moisture increases the thickness of anaerobic zone and enhances CH_4 production (Yavitt et al., 1995). In Central Kalimantan, Indonesia, it was reported that the GWL boundary for soil CH_4 efflux/influx was –20 cm in an undrained peat swamp forest (Jauhiainen et al., 2008). In this study, however, FCH_4 measured above the forest canopy was always positive, even though GWL was lower than –20 cm (Fig. 5). The net CH_4 emissions measured even in drier conditions (GWL < –20 cm) was attributable to plant-mediated transport and possibly termite emissions, which are discussed later. The different responses of CH_4 emissions to GWL could be attributed to the differet peat properties of the two regions. The peat types in Central Kalimantan and Sarawak are classified as 'inland peat' and 'coastal peat', respectively, and these are different in age and carbon accumulation rates (Dommain et al., 2011; Kurnianto et al., 2015).

Seasonal variation of soil temperature was much smaller in tropical peatland than in temperate and boreal peatlands. In general, there is a positive relationship between CH_4 production and soil temperature in temperate and boreal peatlands (Jackowicz- Korczyński et al., 2010; Olson et al., 2013; Song et al., 2015). In this study, however, FCH_4 was negatively correlated with soil temperature despite its narrow seasonal range. This is probably because of the negative correlation of soil temperature with GWL.

4.2. Comparison of annual CH_4 emissions with other ecosystems

In tropical peat swamp forest, soil CH_4 flux has been measured by static chambers. This study shows the first ecosystem-scale CH_4 flux measured by the eddy covariance technique. Annual FCH_4 of the tropical peat swamp forest was estimated to be 7.5–10.8 $g\,C\,m^{-2}\,yr^{-1}$, of which 9.8–10.8 $g\,C\,m^{-2}\,yr^{-1}$ would be the most reliable estimate of annual CH_4 emissions (Table 2). The annual FCH_4 was more than seven times higher than the annual soil CH_4 emissions reported by previous chamber studies from tropical peatlands (Jauhiainen et al., 2005; Melling et al., 2005; Jauhiainen et al., 2008; Sangok et al., 2017) (Table 3). The large difference in annual emissions from tropical peatland between this and previous studies is mainly attributable to the following reasons.

Annual FCH_4 measured by the eddy covariance technique accounts for the CH_4 flux from/to hollows, hummocks, tree stems, termites, etc. It is difficult to determine a spatially-representative soil CH_4 flux by the chamber technique because of uneven microtopography and complex water conditions. For example, soil CH_4 emissions are higher from hollows than hummocks (Pangala et al., 2013). In our study site, there are many ponded hollow areas, and some of the hollow areas were water-filled even in the dry season. Gap-filled FCH_4 in the dry month (July 2014) accounted for 4.3–6.1% of annual CH_4 emission. These hollow areas could be hot spots of CH_4 emissions.

It is known that net emission rates of CH_4 are greatly influenced by the transport of CH_4 through herbaceous plants in boreal and temperate peatlands (Waddington and Roulet, 1996; Ding et al., 2003; Frenzel and Karofeld, 2000). Also, tree species growing on waterlogged soils transfer CH_4 produced in the soil and emit the CH_4 from their stems to the atmosphere (Terazawa et al., 2007; Gauci et al., 2010; Rice et al., 2010; Pangala et al., 2013, 2015). With root systems penetrating anoxic soil horizons, plants transport CH_4 via their aerenchyma to the atmosphere, which bypass zones of aerobic methanotrophy (Bridgham et al., 2013). This process is especially important during the dry season when the unsaturated soil zone is thicker. In addition, Wang et al. (2016) found that CH_4 emitted from tree stems was partly produced in heartwood. On a global scale, CH_4 emission from woody vegetation was estimated to be about 60 $Tg\,CH_4\,yr^{-1}$, which is equivalent to about 10% of the global CH_4 source (Rice et al., 2010). In the tropics, Pangala et al. (2013) reported that tree stems emit greater amount of CH_4 than ground surfaces, accounting for 62–87% of total ecosystem CH_4 efflux from a relatively undisturbed tropical peat swamp forest in Central Kalimantan, Indonesia. They showed that one of the dominant tree species which emit CH_4 was *Shorea balangeran*. At our study site, *Shorea albida*, which is classified into the same genus as *Shorea balangeran*, was dominant. Thus, *Shorea Albida* probably have contributed significantly to the annual FCH_4. Recently, it was found that trees growing on the floodplain in Amazonia emit CH_4 abundantly from their stems (Pangala et al., 2017). The CH_4 efflux from Amazonian tree stems was up to 200 times larger than emissions reported for the tropical peat swamp forest in Indonesia (Pangala et al., 2013). The large difference would be attributable to a higher CH_4 production potential of the sedimentary soil in the floodplain forest. In addition, termite is a host of methanogen and one of the most important biogenic CH_4 sources, which accounts for 2 to 10% of global CH_4 emissions (Rasmussen and Khalil, 1983; Fraser et al., 1986; Cicerone and Oremland, 1988). In Sarawak, dominant termite species in peat swamp forest nest aboveground (Vaessen et al., 2011) and emit CH_4 (Martius et al., 1993; Jeeva et al., 1999). The studies for tropical peatland shown in Table 3 did not measure CH_4 flux from tree stems and termites and consequently underestimated annual CH_4 emissions. Furthermore, lower GWL in Jauhiainen et al. (2008) and Sangok et al. (2017) may have increased substrate oxidation and reduced availability for methanogenesis. In the studies, GWL dropped below –1 m in the dry season, which was more than three times lower than the lowest GWL in this study. A large amount of substrate was probably oxidized into CO_2 in the low GWL conditions (Hirano et al., 2014), which would have resulted in lower substrate availability for CH_4 production in the following wet season.

In comparison with studies using the eddy covariance technique in other climatic regions (Table 3), the annual CH_4 emissions of this study was comparable with that of a subarctic oligotrophic fen (Rinne et al., 2007), was lower than those of a temperate poor fen (Olson et al., 2013), a temperate alpine peatland on silty clay loam (Song et al., 2015) and a subarctic mosaic of ombrotrophic and minerotrophic peatlands (Jackowicz- Korczyński et al., 2010), and was higher than those of subarctic fens (Hargreaves et al., 2001; Hanis et al., 2013) and an arctic fen (Tagesson et al., 2012). The comparison indicates that the tropical peat swamp forest is a moderate CH_4 source to the atmosphere despite hot and humid climate. In tropical peat swamp forest, diffusive CH_4 efflux from saturated peat is effectively oxidised by bacteria in the shallow aerobic peat layer (Couwenberg et al., 2010). Also, substrate for CH_4 production is insufficient in woody peat with much lignin in ombrotrophic conditions (Jauhiainen et al., 2016; Pangala et al., 2013). Moreover, the oxygen supply through the roots of swamp trees contributes to CH_4 oxidation (Adji et al., 2014). These facts would be reasons why annual CH_4 emissions from tropical peat swamp forest were relatively low.

5. Conclusions

We have conducted the first eddy covariance measurement of CH_4 flux above a tropical peat swamp forest. The findings of this study can be summarized as follows:

- FCH_4 varied seasonally in relation with GWL or soil moisture with the highest value in the rainy season, when GWL rose aboveground. Even in the driest month, when GWL was averaged at –30 cm, the swamp forest remained as a CH_4 source.
- On a daily basis, FCH_4 was positively associated with GWL or soil moisture in a quadratic form.
- Annual CH_4 emissions were more than seven times larger than annual soil CH_4 emissions measured by the chamber technique from tropical peatlands. The large discrepancy in CH_4 emissions could be attributable to aboveground CH_4 emissions from tree stems, which were not covered by the previous studies.
- Although the annual emissions do not exceed those from mid- and high-latitude peatlands, the result suggests that tropical peat swamp forest can be one of the major natural CH_4 sources in the tropics.

Different types of tropical peat swamp forest are distributed in zonation on a peat dome. Therefore, to evaluate the contribution of tropical peat swamp forest to global CH_4 cycles, further studies are necessary to measure FCH_4 separately in each forest type.

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