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EDDY COVARIANCE MEASUREMENT OF METHANE FLUX ABOVE A PRIMARY TROPICAL PEAT SWAMP FOREST IN SARAWAK, MALAYSIA

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SUMMARY

Tropical peat swamp forest is one of the world's most important terrestrial ecosystems, in which both swamp forest and peat soil have evolved together over millennia, because it has accumulated huge amount of carbon as peat. In recent years, considerable attention has been devoted to understand the role of this ecosystem in amplifying global warming. Owing to a significant amount of carbon stock, waterlogged, and associated anaerobic conditions, tropical peatlands may represent a potential source of methane (CH_4). However, there are a few studies on CH_4 flux based on periodic measurement, and no study on continuous CH_4 flux measurement in tropical peat swamp forest. Thus, we started CH_4 flux monitoring in 2011 above a primary tropical peat swamp forest in Sarawak, Malaysia, using the eddy covariance technique. Using field data from January 2014 to July 2015, ecosystem-scale CH_4 exchange was assessed. The tropical peat swamp forest showed net emissions of CH_4 with a mean value of 18.1 n mol m^{-2} s^{-1} for 19 months. Monthly mean CH_4 flux was always positive. On the diurnal timescale, CH_4 flux was positive during daytime and night time where peak CH_4 flux occurs in the early morning. The CH_4 emissions from this ecosystem were mainly controlled by groundwater level (GWL) and soil water content (SWC). Both GWL and SWC were positively (both r = 0.41 and 0.39, $P < 0.001$) correlated with CH_4 flux.

Keywords: *Peatland, eddy covariance technique, open-path CH_4 analyser, diurnal variation, groundwater level*

INTRODUCTION

Tropical peat swamp forest is a unique dual ecosystem, which consists of both tropical rainforest and tropical peatland that exist in high humidity and acidic waterlogged conditions (Melling *et al.,* 2007). The co-existence of tropical rainforest and peatland has accumulated huge amount of soil carbon over the millennia (Page *et al.*, 2004). It has been estimated that about 44.1 Mha of peatland is distributed in the tropics, of which 24.8 Mha is located in Southeast Asia. The amount of carbon in this region accounts for 11-14% of global peat carbon pool (Page *et al.,* 2011). Being an immense carbon store, tropical peatlands play an important role in the global carbon cycle (Müller *et al.,* 2015).

After carbon dioxide (CO_2) and nitrous oxide, methane (CH_4) is another important greenhouse gas that contributed significantly to global warming. Over a century, CH_4 is 25 times more effective than CO_2 at trapping heat in the atmosphere (IPCC, 2007). Its concentration has increased by 150% since the pre-industrial era and currently contributes to 20% of the enhanced greenhouse effect (IPCC, 2007). Due to the significant amount of carbon stock in the soil, tropical peatlands may represent a potential source of CH_4 (Inubushi *et al.,* 2007).

Measurement of greenhouse gas emissions to the atmosphere has largely relied on the chamber method, especially with closed chamber systems (Yu *et al.,* 2013). The chamber method is particularly suitable for point measuring of trace gas emissions in small scale field experiments, but the spatial and temporal variability induce this method become time consuming and labour intensive for large field scale experiments (Wang *et al.,* 2012). Thus, the tower-based micrometeorological approaches such as the eddy covariance technique have been used to measure greenhouse gas flux with the advantage of representing a larger area in the field (Yu *et al.,* 2013), leading to measurements that are more representative of the ecosystem as a whole. This approach also provides minimal disturbance on the measured ecosystem and possibility to measure long, more or less continuous, time series (Rinne *et al.,* 2007).

In tropical peat swamp forest, however, there are a few studies on CH_4 flux based on periodic measurements by the chamber method (Hirano *et al.,* 2009; Inubushi *et al.,* 2007; Melling *et al.,* 2005), and no study is found on continuous CH_4 flux measurement. Therefore, we have measured CH_4 flux above a primary tropical peat swamp forest using the eddy covariance technique with an open-path CH_4 analyser (LI-7700). Using the continuous data from 1 January 2014 to 31 July 2015, we quantify CH_4 flux on an ecosystem scale, examine its diurnal and seasonal variations and determine the environmental factors that influence CH_4 flux.

MATERIAL AND METHODS

Site description

The study site is a primary tropical peat swamp forest located in Maludam National Park, Sarawak, Malaysia (01º27‘14.8”N, 111º8‘45.3”E). The forest is classified as Alan Batu Forest dominated by *Shorea albida* with an average height of 30 m and dense understory vegetation (*Pandanus tectorius)*. The climate at the study site is equatorial, characterized by consistently high temperature, high humidity, and abundant precipitation throughout the year. Precipitation is generally higher during November-March and the lowest in July-August. Groundwater level (GWL) is typically high and rises aboveground during the wettest period. A 40-m-tall tower was built at the study site with a fetch of 600 to 1000 m in all directions. The topography is almost flat with a elevation of about 8.5-9 m above mean sea level and peat depth of about 10 m.

Measurement of CH_4 flux and environmental variables

Fluxes of energy, CO_2 and CH_4 were measured by the eddy covariance technique using a 3D sonic anemometer/thermometer (CSAT3, Campbell Scientific Inc.), an open-path CO_2/H_2O analyser (LI-7500A, Li-Cor Inc.), and an open-path CH_4 analyser (LI-7700, Li-Cor) installed at the tip of a 1-m-long boom projecting towards the predominant winds from southeast at a height of 41 m. The signals of the sensors were sampled at a frequency of 10 Hz using a data logger (CR3000, Campbell).

In addition, downward and upward shortwave and longwave radiation components were measured at 41-m height using a radiometer (CNR4, Kipp & Zonen). Air temperature and relative humidity were measured at 11 m and 41 m using temperature and relative humidity probes (CS215, Campbell). Wind speed and wind direction were measured at 41 m height using a 3-cup anemometer and wind vane (01003-5, R.M. Young Company Young). Soil temperature was measured at a depth of 10 cm using thermocouple thermometers. Volumetric soil water content was measured in the top 30-cm-thick layer using TDR sensors (CS616, Campbell). Precipitation was measured at 1 m above the ground using a tipping-bucket rain gauge (TE525, Campbell). All the environmental variables were measured every 10 s and recorded every 5 min. Groundwater level (GWL) was recorded on a half-hourly basis using a GWL logger (HOBO, Onset). In this study, data measured from 1 January 2014 to 31 July 2015 were used for analysis.

Data Processing

From eddy covariance raw data, half-hourly mean CH_4 flux was calculated using the Flux Calculator software (Ueyama *et al.,* 2012). The flux values were corrected using the modified WPL equation (LI-COR, 2010). Net ecosystem CH_4 exchange was calculated as the sum of the CH_4 flux and the change in CH_4 storage in the air space below the flux measurement height. To avoid flow distortion by the tower, the CH_4 flux data were excluded when wind direction was within 0° to 30° and 280° to 360°. The stationarity and turbulence conditions of CH_4 flux were checked using the criteria of Foken and Wichura (1996). The threshold to screen out the CH_4 flux data based on the absolute value of skewness and kurtosis were set at 3.6 and 14.4, respectively. The CH_4 fluxes corresponding to relative signal strength indicator (RSSI) values less than 20% (due to rain, signal dropout, instrument malfunction, etc) were filtered out. As a result, 47.9% of CH_4 flux data remained after the quality control.

RESULTS AND DISCUSSION

Seasonal and diurnal variations

Figure 1 illustrates the ensemble averaged normalized daytime (0800 – 1600) cospectra of vertical wind speed and air temperature ($w'T'$) and CH_4 density ($w'CH_4'$) against natural frequency (n). In the inertial subrange, $w'CH_4'$ does not exhibit a slope close to the ideal one (-4/3 power law), and the cospectra loss started at n = 0.2. The high frequency loss of CH_4 flux was corrected using the analytical model of Massman (2000, 2001).

The mean half hourly CH_4 flux from January 2014 to July 2015 was 18.1 n mol m^{-2} s^{-1} whereas the annual mean of CH_4 flux for 2014 was 17.8 n mol m^{-2} s^{-1}. CH_4 flux was positive on a half-hourly basis with a peak of 49.1 n mol m^{-2} s^{-1} in the early morning at around 0800 to 0830 (Figure 2). The seasonal variations in monthly means of measured CH_4 flux is shown in Figure 3. In general, CH_4 flux was higher in the wet season than in the dry season. CH_4 flux was 22.3 and 15.8 nmol m^{-2} s^{-1}, on average, in the wet (October to March) and dry season (April to September), respectively.

The ecosystem-scale CH_4 flux was substantially higher than -0.11 - 0.19 n mol m^{-2} s^{-1} reported by Melling *et al.* (2005) but comparable to 19 n mol m^{-2} s^{-1} reported by Inubushi *et al.* (1998) for mixed peat swamp forest and secondary tropical wetland forest, respectively, which were measured with the closed-chamber technique. Pangala *et al.* (2012) reported that tree stems emit greater amount of CH_4 than the soil surfaces, accounting for 62 - 87% of total ecosystem CH_4 flux from a relatively undisturbed tropical peat swamp forest. During night time, CH_4 was stored in the forest floor, rather than being mixed into the overlying atmosphere. The early morning peak in half-hourly CH_4 flux is due to the flushed out of nocturnally stored CH_4 as turbulent mixing is enhanced after sunrise.

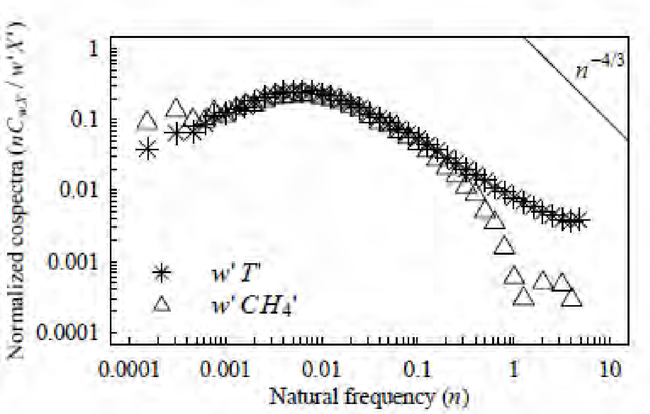

Figure 1: Ensemble averaged normalized daytime cospectra for *w'T'* and *w'CH₄'*; the straight line represents the -4/3 power law.

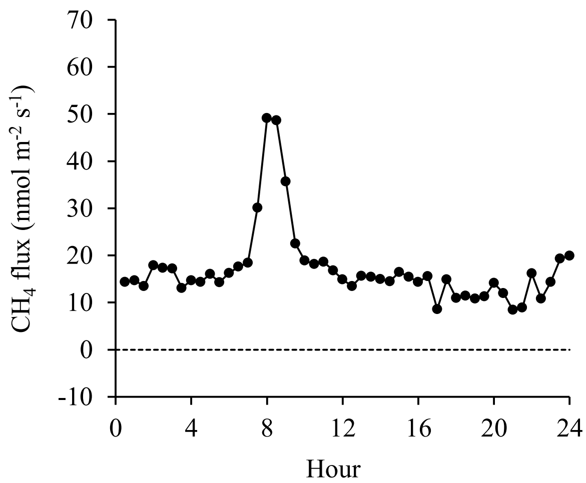

Figure 2: Ensemble-mean diurnal variation in measured CH_4 flux from January 2014 to July 2015.

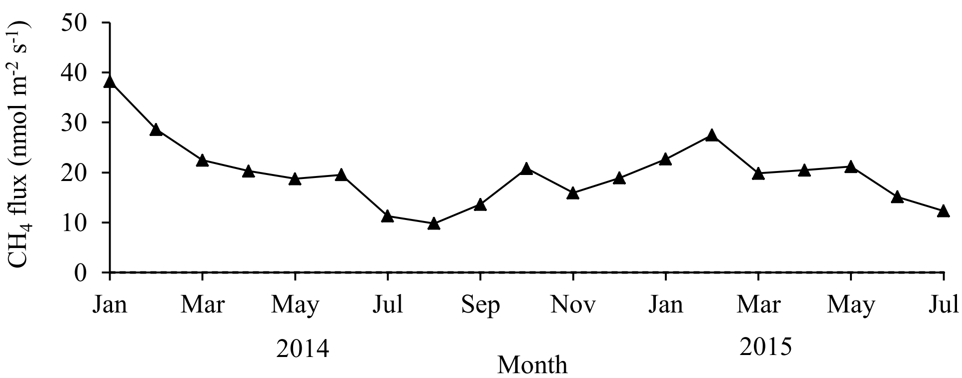

Figure 3: Variations in monthly mean of measured CH_4 flux.

Driving factors of methane flux

Based on the regression analysis, vapor pressure deficit (VPD), air temperature (T_a), soil temperature (T_s), GWL, and soil water content (SWC) showed significant linear relationships ($P < 0.001$) with CH_4 flux on a daily basis. The relationships are positive against GWL and SWC, whereas negative against VPD, T_a, and T_s. Pearson correlation coefficient (r) for GWL was higher than SWC. The influence of GWL on CH_4 flux was most distinct in driest period (July and August) when the GWL was lowest. Figure 4 indicates the linear relationships of CH_4 flux with GWL and SWC. Methanogenesis is the process of microbial CH_4 production under the anaerobic conditions, as a result of fermentation (van Noordvijk *et al.,* 2004). Increase in GWL and SWC would lead to oxygen depletion in the soil and consequently favours the methanogenesis. Thus, the CH_4 emissions from this ecosystem were primarily controlled by GWL and SWC. Generally, there is a positive relationship between CH_4 production and T_s (Wang *et al.,* 1995). However, the T_s was negatively correlated with CH_4 flux in this study (r = - 0.26). This is probably due to the strong negative correlation between SWC and T_s (r = - 0.81).

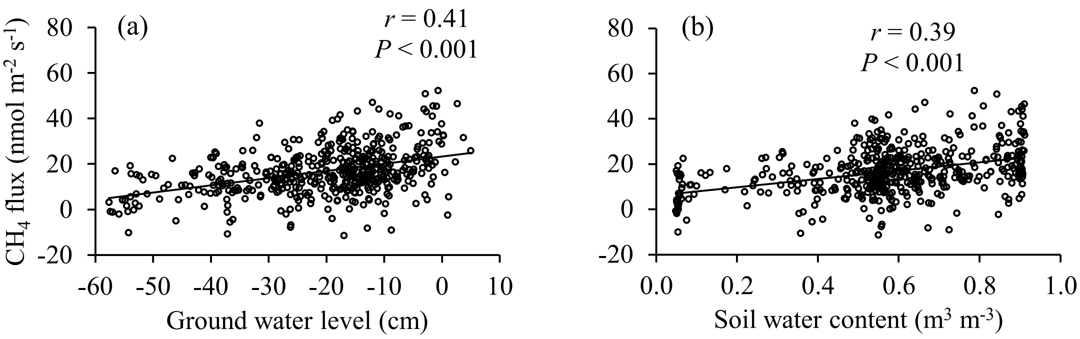

Figure 4: Relationships between CH_4 flux and environmental variables (GWL and SWC) on a daily basis.

CONCLUSION

This study is the first continuous CH_4 flux measurement above the tropical peat swamp forest using eddy covariance technique. The outcomes of this study enable us to have a better understanding of CH_4 flux and its driving factors in tropical peat swamp forest ecosystem. CH_4 flux showed net emissions on an ecosystem scale. The factors influencing the CH_4 emissions from this ecosystem were GWL and SWC.

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