Methane balance of tropical peat ecosystems in Sarawak, Malaysia

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Date of oral examination : 02/08/2018

Date of approval :
Abstract

Tropical peatlands of Southeast Asia, widely distributed in Indonesia and Malaysia, are a globally important carbon reservoir, storing an enormous amount of soil organic carbon as peat. In recent decades, however, the peatlands have been threatened with rapid land cover changes, predominantly into industrial plantations of oil palm and pulpwood. Owing to the huge soil carbon stock, high groundwater level (GWL) and high temperature, tropical peatlands potentially function as a significant source of methane (CH$_4$) to the atmosphere. However, chamber studies of soil CH$_4$ flux have reported that CH$_4$ emissions from tropical peat swamp ecosystems were negligible. On the other hand, recently, it was reported that some tree species growing in peat swamp forest 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 study, we measured ecosystem-scale CH$_4$ flux continuously above three different tropical peat ecosystems in Sarawak, Malaysia for three years from February 2014 to January 2017. This is the first study applying the eddy covariance technique in tropical peat ecosystems. The three sites were different in disturbance; namely an undrained peat swamp forest (UF), a relatively disturbed secondary peat swamp forest (DF) and an oil palm plantation (OP) established on peat after deforestation. The objectives of this study were to: (1) quantify the net ecosystem exchange of CH$_4$ ($F_{CH4}$) of each site; (2) examine the responses of $F_{CH4}$ to environmental factors; and (3) compare $F_{CH4}$ among the three ecosystems and discuss the inter-site difference of CH$_4$ balance.
The \( F_{\text{CH}_4} \) was determined half-hourly as the sum of eddy \( \text{CH}_4 \) flux and \( \text{CH}_4 \) storage change and summed up annually after gap filling. Daily mean \( F_{\text{CH}_4} \) was positively correlated to GWL in UF and DF, in which GWL governed the production and oxidation of \( \text{CH}_4 \) in peat. On the other hand, \( F_{\text{CH}_4} \) was almost independent of GWL in OP, in which GWL was lowered by drainage. Monthly mean \( F_{\text{CH}_4} \) was always positive even in drained OP, meaning \( \text{CH}_4 \) sources. Mean annual \( \text{CH}_4 \) emissions (± 1 SD) were 8.46 ± 0.51, 4.17 ± 0.69 and 2.19 ± 0.21 g C m\(^{-2}\) yr\(^{-1}\), respectively, in UF, DF and OP. There was a significant difference (\( P < 0.001 \)) among the sites. The annual \( \text{CH}_4 \) emission was highest in UF with the highest GWL and lowest in water-managed OP. The inter-site difference was explained considerably by GWL from a significant positive exponential relationship (\( P < 0.001 \)). The ecosystem-scale \( \text{CH}_4 \) emission from UF was lower than those from mid-latitude peat ecosystems, though it was much higher than soil \( \text{CH}_4 \) emissions measured by the chamber technique in tropical peat swamp forests. The difference was probably due to \( \text{CH}_4 \) emissions from tree stems, which were not measured in the soil chamber studies.

A significant positive relationship was found between \( F_{\text{CH}_4} \) and GWL on monthly and annual bases, including all data from the three sites. The positive relationship indicates that the conversion of a peat swamp forest to an oil palm plantation decreases \( \text{CH}_4 \) emissions, because the land conversion accompanies drainage. However, the decrease of \( \text{CH}_4 \) emissions would be insufficient to offset the increase of carbon dioxide emissions through oxidative peat decomposition. The oil palm plantation drained deep to −62 cm on average still functioned as a small \( \text{CH}_4 \) source probably because of high \( \text{CH}_4 \) emissions from ditches.
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Chapter 1

Introduction

1.1 Background

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). Among all the peatlands, tropical peatlands have been regarded as one of the most important terrestrial ecosystems in term of carbon storage. More than 11% of global peatland area is occupied by tropical peatland (Page et al., 2011b; Dargie et al., 2017). Large areas of tropical peatland exist in coastal lowlands in Southeast Asia (Figure 1.), where about 20.7 Mha in Indonesia and 2.6 Mha in Malaysia (Page et al., 2011b). These peatlands were formed through the Holocene as a result of coexistence of swamp forest vegetation and underlying peat, and most of them were started between 7000 and 4000 years BP (Dommair et al., 2011). Holocene peat carbon accumulation rates from 26 sites in the tropics (Southeast Asia, South America and Africa) was averaged at 12.8 g C m$^{-2}$ yr$^{-1}$ despite high accumulation rates of 77 g C m$^{-2}$ yr$^{-1}$ was reported from coastal peat domes in Peninsular Malaysia, Sumatra and Borneo (Yu et al., 2010; Dommair et al., 2011). The amount of carbon accumulated in tropical peatlands was estimated at about 88.6 Gt carbon, with 68.5 Gt carbon in Southeast Asia (Page et al., 2011b). In addition, a recent study discovered a large peatland area of about 14.6 Mha in Congo Basin (Dargie et al., 2017). Owing to the huge carbon stock in the soils, tropical peatlands could be a potential source of methane (CH$_4$).
Tropical peatland is generally low-lying having dome-shaped surface with greater peat depth towards the centre of the peatland (Melling and Hatano, 2004) which exists in an acidic waterlogged conditions. 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 Selunser and Padang Keruntum forests from the edge (Anderson, 1961; Phillips, 1998). However, this sequence is different from 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, greenhouse gas (GHG) dynamics could be heterogeneous in these zonal communities.
Methane is the second most important GHG, with a global warming potential 28 times greater than carbon dioxide (CO$_2$) over a century (Milich, 1999; IPCC, 2013). Atmospheric CH$_4$ arises from both anthropogenic and natural sources (IPCC, 2013). The anthropogenic sources involve rice agriculture, livestock, landfills and waste treatment, biomass burning, and fossil fuel combustion. The natural sources are such as wetlands, oceans, forests, fire, termites and geological sources. On a global scale, the CH$_4$ emissions were estimated at about 500–600 Tg CH$_4$ yr$^{-1}$ (Lelieveld et al., 1998; Wang et al., 2004; Bruhwiler et al., 2014). A large part of the global CH$_4$ emissions were from natural sources, mainly wetlands (Denman et al., 2007). Through data synthesis, the CH$_4$ emission from natural wetlands based on the bottom-up estimation approach was 217 Tg CH$_4$ yr$^{-1}$ for 2000-2009 (Kirschke et al., 2013). Also, the bottom-up approach in Kirschke et al. (2013) showed that the CH$_4$ emissions from natural wetlands are highly uncertain, with a range of 177–284 Tg CH$_4$ yr$^{-1}$. Due to high uncertainty, more wetland CH$_4$ flux measurements are required to accurately estimate the global CH$_4$ balance.

The 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). In addition, tropical zone (30° N–30° S) was reported as major CH$_4$ emission source among global terrestrial ecosystems from northern polar to southern temperate zones (Tian et al., 2015). 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 tropical peat ecosystem.
In tropical peatlands, CH₄ 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 CH₄ efflux is higher on hollows (Pangala et al., 2015). Also, Pangala et al. (2013) reported that dominant trees in tropical peat swamp forest in Indonesia emitted a considerable amount of CH₄ from their stems. Furthermore, there are CH₄-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 CH₄ is not emitted only from the soil surface but also from tree stems and termites, which causes a vertical variation in CH₄ flux.

Measurement of CH₄ 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 CH₄ 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 (~103–105 m²) (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 CH₄ flux on multiple time scales (Rinne et al., 2007).

In middle- and high-latitude peat ecosystems, many studies on CH₄ flux have been conducted by the eddy covariance technique (e.g. Rinne et al., 2007; Jackowicz-Korezyński et al., 2010; Nadeau et al., 2013; Olson et al., 2013; Song et al., 2015). In tropical peatland,
however, there are only a few soil chamber studies (Melling et al., 2005b; 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. However, their studies only measured soil CH$_4$ emission periodically and would be insufficient to assess CH$_4$ emissions from a whole ecosystem.

Methane emissions from middle and high latitude peatlands are strongly controlled by temperature, groundwater level (GWL), substrate availability and vegetation type (Hargreaves et al., 2001; Rinne et al., 2007; Jackowicz-Korczyński et al., 2010; Schrier-Uijl et al., 2010; Hanis et al., 2013; Olson et al., 2013; Song et al., 2015). On the other hand, tropical peatlands are constantly subject to high temperature prevailing throughout the whole year (Jauhiainen et al., 2005; Melling et al., 2005b; Hirano et al., 2009) in which the influence of temperature on CH$_4$ emission is limited (Villa and Mitsch, 2014). Hydrology factors regulating the CH$_4$ emission from tropical peatlands are groundwater level (GWL) and soil moisture (Furukawa et al., 2005; Inubushi et al., 2005; Melling et al., 2005b; Wong et al., 2018). The GWL and soil moisture determine the depth at which aerobic and anaerobic conditions occur in soils, which in turn, control the methanogenic (production) and methanotrophic (oxidation) processes (Yavitt et al., 1995; Nykänen et al., 1998). Even the CH$_4$ can be produced throughout the peat profile, but net emission is limited by oxidation in aerated surface layers (Wright et al., 2011).

In recent decades, Southeast Asian peatlands have undergoing rapid land cover changes, predominantly into monoculture plantations. Conversion of tropical peat swamp forests into monoculture plantations of oil palm or pulpwood plantations has become a huge concern for carbon emissions in Southeast Asia (e.g. Melling et al., 2005c; Germer and
Sauerborn, 2008; Agus et al., 2009; Page et al., 2011a; Carlson et al., 2012; Jauhiainen et al., 2012; Gaveau et al., 2014; Carlson et al., 2015; Miettinen et al., 2017). In 2015, the area of industrial plantations (mainly oil palm and pulp wood) of Peninsular Malaysia, Sumatra and Borneo had increased to 4.3 Mha, and nearly doubled since 2007 (Miettinen et al., 2016). Land conversion with drainage on peatlands lowers the groundwater level (GWL), enhancing soil aeration and intensifies peat carbon loss (Hooijer et al., 2012). On the contrary, drainage decreases thickness of anaerobic soil layer which may reduce the CH$_4$ emission (Melling et al., 2005b). Land cover change of tropical peat swamp forests is generally studied with the CO$_2$ emissions (e.g. Melling et al., 2005c; Hirano et al., 2012; Hirano et al., 2014; Husnain et al., 2014; Itoh et al., 2017) while the study with CH$_4$ emission is very limited.

1.2 Objectives

To our knowledge, there is still no study reporting the long-term CH$_4$ fluxes measurements with the eddy covariance technique from tropical peat ecosystems. Thus, it is essential to quantify the CH$_4$ balance of tropical peat ecosystems from field measurement to understand its contribution to tropical CH$_4$ budget. To addresses this knowledge gap, we measured CH$_4$ flux above three different tropical peat ecosystems in Sarawak, Malaysia from February 2014 to January 2017 (three years). The sites are representing 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 are to:

i) quantify the net ecosystem exchange of CH$_4$ ($F_{CH_4}$) in each ecosystem, and examine its diurnal and seasonal variations;

ii) determine the responses of $F_{CH_4}$ to environmental variables;
iii) compare CH$_4$ flux among the three ecosystems and discuss the inter-site difference of CH$_4$ balance.

The outcomes from this study will contribute to a better assessment of F$_{CH4}$ for tropical peat ecosystems.

1.3 Thesis outline

This thesis is divided into seven chapters. All of the work presented here are to be published as a research paper. However, a version of Chapter 3 with different title and study period from February 2014 to July 2017 (18 months) has been published as an individual paper in Agricultural and Forest Meteorology. Chapter 1 is a general introduction with an overview of tropical peatlands, methane (CH$_4$) fluxes, measurement techniques, land conversion and objectives. Chapter 2 provides description for study sites, eddy covariance system, environmental variables and data processing. Chapter 3, 4 and 5 give the results of CH$_4$ fluxes for UF, DF and OP, respectively. Chapter 6 discusses the CH$_4$ fluxes of each study site and comparison among them. Conclusions and recommendations of this thesis were presented in Chapter 7.

1.4 Publications


Chapter 2
Material and methods

2.1 Site description

This study was conducted in three different ecosystems on coastal peat (Dommair et al., 2011): 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 (Figure ). Both UF and DF are located in Maludam Peninsula (Betong division) and about 29 km apart each other. The Maludam Peninsula is bordered by the Batang Lupar and Batang Saribas Rivers, which flow into the South China Sea. The OP is located in Sibu division and near to Rajang River, with a distance of more than 100 km away from the peninsula. The climate of the region is equatorial and characterized by consistently high temperature, high humidity and abundant precipitation all year round. Mean annual precipitations for 10 years (2005–2014) at local rainfall stations near UF, DF and OP were 3201 ± 614, 3358 ± 465 and 2797 ± 224 mm yr⁻¹ (mean ± 1 standard deviation (SD)), respectively. At UF and DF, GWL are typically high or rises aboveground (Figure 2.) during the wettest period from December to January. Mean annual air temperature (Tₐ) (± 1 SD) in the same period was 26.5 ± 0.2°C at the nearest meteorology station in Kuching International Airport.
Figure 2.1 Map of the sites.

Figure 2.2 GWL rises aboveground during the wettest period at (a) UF and (b) DF.
2.1.1 Undrained peat swamp forest (UF)

The UF is part of the Maludam National Park (43,147 ha) which has been gazetted as a totally protected peat swamp forest area since 2000, and with minimal forest disturbance (Wong et al., 2018). Currently, the national park remains as the largest natural peat swamp forest in Sarawak. There are four zonal communities in the national park, namely Mixed Peat Swamp, Alan Batu, Alan Bunga and Padang Alan forests (Figure ) (Melling, 2016), and their description is shown in Table . We treated UF as the most natural ecosystem of peat swamp forest in this study. The UF is in the zonal community of 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). It is generally located at the shoulder of the peat dome between Mixed Peat Swamp and Alan Bunga forests (Figure ).

Terrain is generally flat with an elevation of 9 m above mean sea level, and with a peat depth of 10 m (Table ). Forest structure is mixed, and the canopy is uneven with a height of 35 m (Figure a). Some trees were prominently emerged from the canopy. The tree density was 1173 trees ha$^{-1}$ in 2016. Plant area index (PAI) has been measured monthly since 2013 using a plant canopy analyser (LAI-2200, Li-Cor Inc., Lincoln, NE, USA) at below the canopy. Mean PAI 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 pandan (Figure a).
Figure 2.3 The zonal communities in Maludam National Park (Melling, 2016; Sangok et al., 2017).
Figure 2.4 The zonal communities across the peat dome at Maludam National Park (Melling, 2016), and UF is in the Alan Batu forest.
Table 2.1 Description of Mixed Peat Swamp, Alan Batu, Alan Bunga and Padang Alan forests (Anderson, 1961; Melling, 2016).

<table>
<thead>
<tr>
<th>Zonal community</th>
<th>Characteristic</th>
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<tbody>
<tr>
<td>Mixed Peat Swamp forest</td>
<td>Located at peatland edge with structure and physiognomy similar to lowland mineral soil dipterocarp rainforest. Structurally most complex, richer in species composition and peat soil is less woody. Dominated by scattered very large trees (&gt; 3.5 m girth) with an uneven and irregular canopy. The trees usually show evidence of being moribund, with stag-head crowns and clearly hollow stems, and heavily buttressed boles. The peat soil is very woody.</td>
</tr>
<tr>
<td>Alan Batu forest</td>
<td>It has an even upper canopy and middle storey is generally absent. The buttresses are much lower and narrower than in Alan Batu forest. The peat soil is very woody.</td>
</tr>
<tr>
<td>Alan Bunga forest</td>
<td>Dense and even canopy forest where it composed of relatively small-sized trees (&lt; 40–60 cm girth) that give the forest a pole-like and xerophytic appearance. These trees are very prone to wind damage. The peat soil is not woody but very fibrous.</td>
</tr>
<tr>
<td>Padang Alan forest</td>
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Table 2.2 Site information of the protected forest (UF), selectively-logged secondary forest (DF) and oil palm plantation (OP).

<table>
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<tr>
<th>Site</th>
<th>Elevation m.s.l (m)</th>
<th>Dominant tree species</th>
<th>Tree density (trees ha$^{-1}$)</th>
<th>Plant area index (m$^2$ m$^{-2}$)</th>
<th>Canopy height (m)</th>
<th>Peat depth (m)</th>
<th>Peat bulk density (g cm$^{-3}$)*</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>UF</td>
<td>9.0</td>
<td><em>Shorea albida, Lithocarpus sp., Litsea sp., Dillenia sp</em></td>
<td>1173</td>
<td>6.4</td>
<td>35</td>
<td>10.0</td>
<td>0.11</td>
<td>Wong et al. (2018)</td>
</tr>
<tr>
<td>DF</td>
<td>8.5</td>
<td><em>Litsea spp., Shorea albida</em></td>
<td>1990</td>
<td>7.9</td>
<td>25</td>
<td>10.0</td>
<td>0.12</td>
<td>Kiew et al. (2018)</td>
</tr>
<tr>
<td>OP</td>
<td>5.5</td>
<td><em>Elaeis guineensis Jacqu.</em></td>
<td>153</td>
<td>3.7</td>
<td>8</td>
<td>12.7</td>
<td>0.24</td>
<td>Ishikura et al. (2018)</td>
</tr>
</tbody>
</table>

*0 to 5-cm-thick surface soil.
**Figure 2.5** The canopies of (a) UF, (b) DF and (c) OP.
Figure 2.6 The floors of (a) UF, (b) DF and (c) OP.
2.1.2 Relatively disturbed secondary peat swamp forest (DF)

The DF is a relatively disturbed peat swamp forest in which the forest has been selectively logged and regrown as a secondary forest (Kiew et al., 2018). Logging was almost terminated in 1980s, and land conversion into oil palm plantations of area surrounding the forest was started in 1990s. The remaining forest area is 2,560 ha. The DF is at the border of Alan Bunga and Padang Alan forests, about 4.6 km away from the Batang Lupar River. The border DF was surrounded by ditches (Figure) of nearby oil palm plantations. Consequently, the GWL of DF is affected by water managements by the ditches, where the closest ditch is at about 1.2 km away. Terrain is generally flat with an elevation of 8.5 m above mean sea level, and the peat depth is 10 m (Table). Forest structure is mixed, and the canopy is uneven with a height of 25 m (Figure b). There were some prominent emergent trees, but less than the UF. Tree density was 1990 trees ha\(^{-1}\) in 2016. Mean PAI was 7.9 m\(^2\) m\(^{-2}\), and no seasonal variation was found in PAI. Microtopography consists of hollows and hummocks covered mostly with leaf litter. The dominant tree species are *Litsea spp.* and *Shorea albida*, and saplings are abundant below the canopy (Figure b).

![Figure 2.7](image)

**Figure 2.7** The ditch at the border of DF with a width of 3 m, and about 1.2 km away from tower.
2.1.3 Oil palm plantation (OP)

A Mixed Peat Swamp forest was converted into an oil palm (*Elaeis guineensis* Jacqu.) plantation in 2004 (Ishikura et al., 2018). During land preparation, ditches (Figure) and water gates were installed to control GWL. The peat was compacted to prevent oil palm trees from leaning and toppling. Terrain is relatively flat with an elevation of 5.5 m above mean sea level, and the peat depth is 12.7 m (Table). The oil palm trees were planted on a triangular grid spacing of 8.5 m between trees, and tree density was 153 trees ha$^{-1}$. The floor was sparsely covered with fern plants (Figure c). In 2014, the oil palm trees were 9 years old with a canopy height of about 8 m. The OP is under first cycle of cultivation as oil palm trees are commonly replanted for every 25–30 years (Basiron, 2007).

![Figure 2.8 The ditch at OP with a width of 3.5 m.](image)
2.2 Peat structure and bulk density

As observed from the peat profiles, peat was studded with many undecomposed woody pieces and cavities at UF and DF (Figs. 2.9a and 2.9b). The peat of OP (Fig. 2.9c) is originated from mixed peat swamp forest which is characterized by the most decomposed and denser peat than the other sites (Melling, 2016). The bulk density of surface soil (0–5cm) was two times higher at OP due to peat compaction than at the other sites (Table 1). The bulk density of UF, DF and OP were 0.11, 0.12 and 0.24 g cm\(^{-3}\), respectively. In theory, the bulk density (Table 2.2) indirectly provides a measure of the soil porosity with low bulk density indicates high porosity. Thus, the soil porosity of UF and DF were much higher than OP.

![Figure 2.9 Peat profiles of (a) UF, (b) DF and (c) OP.](image)

2.3 Eddy covariance and meteorological measurements

Methane flux has been measured above the canopies by the eddy covariance technique (McDermitt et al., 2011) since 2012 along with CO₂, water vapor and heat fluxes. Flux sensors were mounted on towers at the heights of 41 m in UF and DF, and 21 m in OP. At each site, the flux measurement system consisted of a 3D sonic anemometer/thermometer (CSAT3, Campbell Scientific Inc., Logan, UT, USA), an open-path CO₂/H₂O analyser (LI-7500A, Li-Cor Inc., Lincoln, NE, USA), and an open-path CH₄ analyser (LI-7700, Li-Cor Inc.). The sensor separation between CSAT3 and LI7700 was 60 cm. Sensor signal was sampled at 10 Hz using a datalogger (CR3000, Campbell Scientific Inc.). The system was powered by solar energy. To maintain good signal strengths from LI-7700, the upper and lower windows were not only automatically cleaned but also manually done twice a month. The flux towers and eddy flux sensors of all sites are shown in Figure and Figure.

At each site, downward and upward shortwave and longwave radiation components were measured using a radiometer (CNR4, Kipp and Zonen, Delft, the Netherlands). Downward and upward photosynthetically active radiation (PAR) components were measured using quantum sensors (LI-190S, Li-Cor Inc.). Tₐ and relative humidity were measured using temperature and relative humidity probes (CS215, Campbell Scientific Inc.) installed in a 6-plate solar radiation shield (41303-5A, Campbell Scientific Inc.). 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). Precipitation was measured at 1 m above the ground using a tipping-bucket rain gauge (TE525, Campbell Scientific Inc.) at a nearby open space. Soil temperature (Tₛ) was measured at a depth of 5 cm using a platinum resistance thermometer (C-PTWP, Climatec, Tokyo, Japan). 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.). All the environmental variables were measured every 10 s and recorded every 5 minutes with a datalogger (CR1000, Campbell Scientific Inc.). GWL was recorded half-hourly using a piezometer. GWL was defined as a distance from a hollow surface, where the piezometer was installed; a positive GWL represents the water surface to be aboveground, and vice versa. Missing data in GWLs were gap-filled by the tank model (Sugawara, 1979). The meteorological sensors are shown in Figure. The quantum sensor, radiometer, temperature and relative humidity probes and 3-cup anemometer and wind vane were measured at different height on the tower (Table).
Figure 2.10 Flux towers of (a) UF, (b) DF and (c) OP. All tower heights are 41 m.
Figure 2.11 Eddy flux sensors of (a) UF, (b) DF and (c) OP.
Figure 2.12 Meteorological sensors of (a) quantum sensor, (b) radiometer, (c) temperature and relative humidity probes, (d) 3-cup anemometer and wind vane, (e) tipping-bucket rain gauge, (f) platinum resistance thermometer, (g) domain reflectometry (TDR) sensors and (h) piezometer at UF, DF and OP.
Table 2.3 Measurement heights of quantum sensor, radiometer, temperature and relative humidity probes and 3-cup anemometer and wind vane at UF, DF and OP.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Site</th>
<th>UF (m)</th>
<th>DF (m)</th>
<th>OP (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum sensor</td>
<td></td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Radiometer</td>
<td></td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Temperature and relative humidity</td>
<td></td>
<td>40</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>probes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-cup anemometer and wind vane</td>
<td></td>
<td>40</td>
<td>40</td>
<td>20</td>
</tr>
</tbody>
</table>

2.4 Data processing

Half-hourly mean CH$_4$ flux was calculated from raw data using Flux Calculator software (Ueyama et al., 2012). In Flux Calculator, 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. Then, $F_{\text{CH}_4}$ (nmol m$^{-2}$ s$^{-1}$) was calculated as the sum of eddy CH$_4$ flux ($F_C$, nmol m$^{-2}$ s$^{-1}$) and change in CH$_4$ storage ($F_S$, nmol m$^{-2}$ s$^{-1}$) in an air column below the flux measurement height.

$$F_{\text{CH}_4} = F_C + F_S$$
The $F_S$ was calculated from CH$_4$ concentration measured with the open-path analyser for eddy flux measurement above the canopy. The storage changes are especially important at our sites because of high canopies ($\geq$ 8 m). In fact, the $F_S$ should be calculated using CH$_4$ profile data to accurately determine $F_{CH_4}$. 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 $F_S$ was compensated by morning flush, and the bias on daily, monthly and annual sums of $F_{CH_4}$ 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.

2.5 Quality control

A series of quality control procedures was used to eliminate low quality $F_{CH_4}$ data. The relative signal strength indicator (RSSI) is an important indicator of the quality of CH$_4$ flux. Thus, the RSSI threshold of 20% (Wong et al., 2018) was first used to exclude the low-quality data due to dew condensation, rain, dirty windows, etc. Then, the $F_{CH_4}$ data were controlled according to 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, we used the friction velocity ($u^*$) as a criterion to remove the data recorded during low turbulence conditions (Long et al., 2010; Wong et al., 2018). The flux data of each site were rank ordered by $u^*$ and then binned into decile groups (Figure ). According to a method applying multiple regression analysis
(Saleska et al., 2003; Hirano et al., 2007), a $u^*$ threshold for $F_{CH_4}$ was determined to be 0.14 ms$^{-1}$ for UF, whereas no threshold was found for DF and OP.

![Graph of CH$_4$ fluxes](image)

**Figure 2.13** Relationship of CH$_4$ fluxes [net ecosystem CH$_4$ exchange ($F_{CH_4}$), eddy CH$_4$ flux ($F_C$) and CH$_4$ storage change ($F_S$)] with friction velocity ($u^*$) for entire days at (a) UF, (b) DF and (c) OP. Flux data were sorted by $u^*$ and binned into decile groups. Vertical bars denote standard errors.
2.6 Gap filling

After the quality control, the surviving rates of $F_{\text{CH}_4}$ data were 30%, 34% and 29%, respectively, for UF, DF and OP. We used the mean diurnal variation (MDV) method (Falge et al., 2001; Dengel et al., 2011; Hommeltenberg et al., 2014; Jha et al., 2014; Gao et al., 2015; Wong et al., 2018) to fill the gaps of $F_{\text{CH}_4}$. Usually, a moving window of 7 to 14 days is considered appropriate. In this study, because a large amount of data was rejected through the quality control, a longer interval of ±83 days was used. Then, annual $F_{\text{CH}_4}$ was calculated using the gap-filled data. The annual period was defined starting on 1 February and ending on 31 January during the 3 years of February 2014–January 2017.

2.7 Global warming potential (GWP)

We assess the global warming potential (GWP) of DF based on CO$_2$ and CH$_4$. A recent study by Kiew et al. (2018) reported that the DF was a net CO$_2$ sink. However, the CO$_2$ sequestration by DF is potentially offset by CH$_4$ if DF is a CH$_4$ source. We used annual net ecosystem exchange of CO$_2$ from Kiew et al. (2018) to investigate the GWP effect from DF, even though their study period was different from this study. In order to equivalently compare the impact of CO$_2$ and CH$_4$ from DF, annual $F_{\text{CH}_4}$ was converted into equivalent unit with CO$_2$ using GWP factor of 28 (Melling et al., 2005a; IPCC, 2013). The scaling factor of 28 represents the global warming potential for CH$_4$ over a 100-year time horizon. A net GWP was calculated for DF by added the GWP of CH$_4$ and CO$_2$.  

2.8 **Statistical analysis**

Seasonal variation of $F_{CH4}$ and environmental factors were examined on a monthly basis. Statistical analyses were performed using R software (R Core Team, 2017). One-way ANOVA was used to test differences in $F_{CH4}$ and environmental factors between sites. Tukey's Honest Significant Difference (HSD) was used for post-hoc mean comparisons for $F_{CH4}$ and environmental factors among the sites. Welch's t-test was used to test the difference for two-group data. We focused on the responses of $F_{CH4}$ to the environmental factors of GWL, soil moisture, $T_a$ and $T_s$. Pearson’s correlation ($r$) and regression analysis were used to investigate the relationship between $F_{CH4}$ and environmental factors in each site on daily and monthly bases. The significance level ($P$) used is 0.05.
Chapter 3

Methane balance of an undrained peat swamp forest (UF)

3.1 Seasonal and inter-annual variations in environmental variables

During the study period, seasonal variation in monthly precipitation was anomalous in 2014 (Figure 3.a). 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, monthly precipitation suddenly increased up to 441 mm month$^{-1}$. Also, the July 2014 was the driest month over the whole study period. In 2015, the monthly precipitation was much higher in January, February, November and December and lower in March–October. In 2016, the monthly precipitation was much higher in January and relatively constant between February and December, except for July with the lowest value (99 mm month$^{-1}$) in the year. The monthly precipitation was ensemble averaged for the common period of 3 years from February 2014 to January 2017 (Fig. 3.2a). The ensemble mean seasonal variation of UF is almost similar for the 10-year-long record (2005–2014) at local rainfall station near UF (Fig. 3.2b). Annual precipitation was the highest in annual period of February 2015–January 2016 with an annual precipitation of 2833 mm yr$^{-1}$ (Fig. 3.3a). Mean annual precipitation ($\pm$ 1 SD) was 2560 $\pm$ 249 mm yr$^{-1}$, which was 20% less than the mean annual long-term precipitation (2005-2014; $\pm$ 1 SD) of 3201 $\pm$ 614 mm yr$^{-1}$. 
Seasonal variation in monthly GWL was almost similar to that in precipitation (Figs. 3.1a and 3.1b) in which the GWL was positively correlated with monthly precipitation \( r = 0.67; P < 0.001 \). In normal years, GWL of UF was near to or above the soil surface. However, GWL dropped to –30 cm in July 2014 with limited monthly precipitation (44 mm). The monthly GWL was ranges from –30 cm (July 2014) to 12 cm (February 2015). In addition, the GWL was much higher from December to February. Annual GWL showed similar variation as precipitation (Figs. 3.3a and 3.3b). Annual GWL was ranges from –7.6 to –2.4 cm, with a mean annual value (± 1 SD) of –4.9 ± 2.6 cm.

Seasonal variation in soil moisture of the top 30-cm-thick layer was coincident with the rise and fall in GWL (Figs. 3.1b and 3.1c). The minimum soil moisture was 0.09 m\(^3\) m\(^{-3}\) in July 2014 and the maximum was 0.90 m\(^3\) m\(^{-3}\) in February 2016. Annual soil moisture showed an increasing trend during 3 years period, ranged from 0.56 to 0.72 m\(^3\) m\(^{-3}\) (Fig. 3.3c). Mean annual soil moisture (± 1 SD) was 0.65 ± 0.08 m\(^3\) m\(^{-3}\).

Monthly \( T_a \) and \( T_s \) varied narrowly during 3 years period in which \( T_a \) was always higher than \( T_s \) (Figs. 3.1d and 3.1e). Similarly, annual \( T_a \) and \( T_s \) varied narrowly within a range of 0.4°C (Figs. 3.3d and 3.3e). In addition, monthly solar radiation tended to decrease from December to January due to high precipitation (Fig. 3.1f). Annual solar radiation was ranges from 16.8 to 17.6 MJ m\(^{-2}\) d\(^{-1}\) (Fig. 3.3f).
Figure 3.1 Variations in monthly (a) precipitation, (b) groundwater level (GWL) and (c) soil moisture from February 2014 to January 2017. Vertical bars denote standard errors.
Figure 3.1 (continued) Variations in monthly (d) air temperature ($T_a$), (e) soil temperature ($T_s$), (f) solar radiation and (g) gap-filled daily net ecosystem CH$_4$ exchange ($F_{CH4}$) from February 2014 to January 2017. Vertical bars denote standard errors.
**Figure 3.2** Ensemble mean seasonal variations in precipitation at (a) UF (3 years) and (b) local rainfall station near UF (10 years).
Figure 3.3 Variations in annual (a) precipitation (b) groundwater level (GWL), (c) soil moisture, (d) air temperature ($T_a$), (e) soil temperature ($T_s$), (f) solar radiation and (g) gap-filled daily net ecosystem CH$_4$ exchange ($F_{CH4}$) from February (Feb) 2014 to January (Jan) 2017.
3.2 Diurnal variations in CH$_4$ fluxes

Diurnal variations in CH$_4$ fluxes were plotted before and after $u^*$ correction to evaluate the double counting effect (Nakai et al., 2003) due to single point measurement of $F_{CH4}$ and $F_S$ above the canopy. Independent of $u^*$ correction, the diurnal variations in $F_{CH4}$ were very similar to each other, whereas nighttime $F_{CH4}$ was slightly more positive after the $u^*$ correction (Figs. 3.4a and 3.4b). Both $F_{CH4}$ and $F_C$ were always positive and showed a marked peak early in the morning at around 07:30–09:00 (Fig. 3.4b). The peaks of $F_{CH4}$ and $F_C$ were 51 and 87 nmol m$^{-2}$ s$^{-1}$, respectively. Increased in $F_{CH4}$ was lasted from 07:00 to 10:30, which is in parallel with increased in $u^*$ (Fig. 3.5) or turbulent mixing. The early morning peak was due to the flush out of stored CH$_4$ in the forest during the nighttime as turbulent mixing was enhanced after su

![Figure 3.4](image)

**Figure 3.4** Ensemble mean diurnal variations in net ecosystem CH$_4$ exchange ($F_{CH4}$), eddy CH$_4$ flux ($F_C$) and CH$_4$ storage change ($F_S$) from February 2014 to January 2017 (a) before friction velocity ($u^*$) correction and (b) after $u^*$ correction.
Figure 3.5 Ensemble mean diurnal variations friction velocity ($u^*$) from February 2014 to January 2017. Increased in turbulent mixing was started at 07:00.

3.3 Seasonal and inter-annual variations in $F_{\text{CH}_4}$

Mean half-hourly measured $F_{\text{CH}_4}$ (± 1 SD) from February 2014 to January 2017 was 20.7 ± 36.4 nmol m$^{-2}$ s$^{-1}$, indicating that this ecosystem was a net $\text{CH}_4$ source to the atmosphere. On a monthly basis, gap-filled $F_{\text{CH}_4}$ was always positive (Fig. 3.1g). Seasonal variation in gap-filled $F_{\text{CH}_4}$ was similar with GWL and soil moisture (Figs. 3.1b and 3.1c). The $F_{\text{CH}_4}$ was positively correlated with GWL ($r = 0.77; P < 0.001$) and soil moisture ($r = 0.64; P < 0.001$). The seasonal variation of $F_{\text{CH}_4}$ showed a V-shaped variation and generally consistent in all annual periods. Peak $F_{\text{CH}_4}$ occurred in January or February when the GWL was high or above soil surface. Annual $F_{\text{CH}_4}$ in the form of mean monthly values showed a decreasing trend during 3 years period (Fig. 3.3g).
3.4 Responses of $F_{CH_4}$ to environmental variables

Influence of environmental variables on $F_{CH_4}$ was examined using linear or curvilinear regression. To avoid biases due to the morning flush, daily means were used. The daily means of measured $F_{CH_4}$ were determined, only if the number of measured data was more than nine on each day. The relationships of the $F_{CH_4}$ with GWL, soil moisture, $T_a$ and $T_s$ were best-fitted with quadratic regressions (Fig. 3.6). However, the differences in $R^2$ between linear and curvilinear relationships were small within 0.0031 (Table 3.1). More than 5% of variances in $F_{CH_4}$ were explained by GWL and soil moisture which were much higher than $T_a$ and $T_s$. Because the soil moisture was strongly controlled by GWL ($r = 0.92, P < 0.001$), the most important factor controlling the CH$_4$ emission from this site was GWL. The linear relationship suggests that CH$_4$ emissions increase by 3.1 nmol m$^{-2}$ s$^{-1}$ for every 10 cm rise of GWL. On the other hand, the curvilinear relationship indicates that peak CH$_4$ emission was 24.2 nmol m$^{-2}$ s$^{-1}$ at GWL of 30 cm. The $F_{CH_4}$ was negatively associated with $T_s$. This relationship was probably due to a negative correlation between $T_s$ and GWL ($r = -0.67, P < 0.001$) as increased in GWL decreased the $T_s$ and increased the $F_{CH_4}$. 


Figure 3.6 Responses of net ecosystem CH₄ exchange (F(CH₄)) to (a) groundwater level (GWL), (b) soil moisture, (c) air temperature (Tₐ) and (d) soil temperature (Tₛ) on a daily basis. The relationships were determined using measured data and regression curves were drawn.
Table 3.1 Relationships of $F_{CH_4}$ with groundwater level (GWL), soil moisture, air temperature ($T_a$) and soil temperature ($T_s$) on linear and curvilinear bases.

<table>
<thead>
<tr>
<th>Environmental variable</th>
<th>F$_{CH_4}$ (nmol m$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Linear</td>
</tr>
<tr>
<td>GWL (cm)</td>
<td>$y = 0.31x + 21.4$ ($R^2 = 0.0545$)$^*$</td>
</tr>
<tr>
<td>Soil moisture (m$^3$ m$^{-3}$)</td>
<td>$y = 13.2x + 10.7$ ($R^2 = 0.0509$)$^*$</td>
</tr>
<tr>
<td>$T_a$ (°C)</td>
<td>$y = -1.02x^2 + 56.4x - 763.4$ ($R^2 = 0.0226$)$^*$</td>
</tr>
<tr>
<td>$T_s$ (°C)</td>
<td>$y = -2.63x + 78.0$ ($R^2 = 0.0200$)$^*$</td>
</tr>
</tbody>
</table>

$^*$ < 0.01, $^*$ < 0.001

3.5 Annual CH$_4$ balance

Annual $F_{CH_4}$ (annual sum) were 8.87, 8.63 and 7.89 g C m$^{-2}$ yr$^{-1}$, respectively, for the annual periods of February 2014–January 2015, February 2015–January 2016 and February 2016–January 2017. The difference in annual $F_{CH_4}$ among the annual period was within 1 g C m$^{-2}$ yr$^{-1}$. Mean annual $F_{CH_4}$ (± 1 SD) was 8.46 ± 0.51 g C m$^{-2}$ yr$^{-1}$. To examine the effect of the correction, mean annual $F_{CH_4}$ was also calculated without $u^*$ correction and resulted in 7.69 ± 0.29 g C m$^{-2}$ yr$^{-1}$, which was smaller than that with $u^*$ correction by 0.77 g C m$^{-2}$ yr$^{-1}$ (9%).
Chapter 4

Methane balance of a relatively disturbed peat swamp forest (DF)

4.1 Seasonal and inter-annual variations in environmental variables

Seasonal variation in monthly precipitation was anomalous in 2014, with a lowest monthly precipitation in June 2014 (Fig. 4.1a). In 2014, monthly precipitation increased from February to May and suddenly dropped to 55.4 mm month$^{-1}$ in June. Then, the monthly precipitation increased from July to September and stayed relatively constant until the end of the year. In 2015, the monthly precipitation in January, November and December were much higher than February–October. In 2016, the monthly precipitation decreased from January to June and then increased from July to December. Ensemble mean of monthly precipitation for the common period of 3 years from February 2014 to January 2017 is shown in Figure 4.2a. The seasonal variation in ensemble mean of DF is almost similar for the 10-year-long record (2005–2014) at local rainfall station near DF (Fig. 4.2b). Annual precipitation was the highest in annual period of February 2016-January 2017 with an annual precipitation of 2766 mm yr$^{-1}$ (Fig. 4.3a). Mean annual precipitation (± 1 SD) was 2472 ± 254 mm yr$^{-1}$, which was 26% less than the mean annual long-term precipitation (2005–2014; ± 1 SD) of 3358 ± 465 mm yr$^{-1}$.

Seasonal variation in monthly GWL was comparable to the precipitation (Figs. 4.1a and 4.1b). There was a positive correlation between the monthly GWL and precipitation ($r = 0.73$; $P < 0.001$). The GWL was higher in the beginning and end of the years except 2014 due
to anomalous precipitation. The GWL was affected by the water managements of nearby oil palm plantations in which the site was surrounded by the ditches. Consequently, the monthly GWL was drop to below −50 cm (September 2015) and never rose above 0.2 cm (January 2015). In contrast to monthly precipitation, inter-annual variation in GWL was different from precipitation (Figs. 4.3a and 4.3b). Annual GWL was ranges from −23.2 to −19 cm, with a mean annual value (± 1 SD) of −20.8 ± 2.2 cm.

Seasonal variation in soil moisture (30-cm-thick layer) was similar to that in GWL; the minimum was 0.2 m$^3$ m$^{-3}$ in July 2014 and the maximum was 0.88 m$^3$ m$^{-3}$ in January 2015 (Fig. 4.1c). On an annual basis, annual soil moisture showed a decreasing trend during 3 years period, ranged from 0.53 to 0.7 m$^3$ m$^{-3}$ (Fig. 4.3c). Mean annual soil moisture (± 1 SD) was 0.59 ± 0.1 m$^3$ m$^{-3}$.

Similar with UF, monthly $T_a$ and $T_s$ varied narrowly during 3 years period in which $T_a$ was always greater than $T_s$ (Figs. 4.1d and 4.1e). Annual $T_a$ and $T_s$ varied narrowly within a range of 1.2°C (Fig 4.3d and 4.3e). Monthly solar radiation was almost constant and tended to decrease from December to January due to high precipitation (Fig. 4.1f). Annual solar radiation was ranges from 16.6 to 17 MJ m$^{-2}$ d$^{-1}$ (Fig. 4.3f).
Figure 4.1 Variations in monthly (a) precipitation, (b) groundwater level (GWL) and (c) soil moisture and from February 2014 to January 2017. Vertical bars denote standard errors.
Figure 4.1 (continued) Variations in monthly (d) air temperature ($T_a$), (e) soil temperature ($T_s$), (f) solar radiation and (g) gap-filled daily net ecosystem CH$_4$ exchange ($F_{CH4}$) from February 2014 to January 2017. Vertical bars denote standard errors.
Figure 4.2 Ensemble mean seasonal variations in precipitation at (a) DF (3 years) and (b) local rainfall station near DF (10 years).
Figure 4.3 Variations in annual (a) precipitation (b) groundwater level (GWL), (c) soil moisture, (d) air temperature ($T_a$), (e) soil temperature ($T_s$), (f) solar radiation and (g) gap-filled daily net ecosystem CH$_4$ exchange ($F_{\text{CH}_4}$) from February (Feb) 2014 to January (Jan) 2017.
4.2 Diurnal variations in CH$_4$ fluxes

Similar with UF, both $F_{\text{CH}_4}$ and $F_C$ were always positive (Fig. 4.4). However, only $F_C$ showed a marked peak early in the morning (08:00-09:00) due to increase in turbulent mixing (Fig. 4.5). Increased in $F_C$ was lasted from 07:00 to 10:30 with a peak of 48 nmol m$^{-2}$ s$^{-1}$. The $F_S$ would has been underestimated because it was calculated only using CH$_4$ concentration at eddy covariance measurement height. However, the morning flush of $F_C$ was well compensated by decreased storage because there was no morning flush in $F_{\text{CH}_4}$. There was no clear diurnal pattern in $F_{\text{CH}_4}$, and the $F_{\text{CH}_4}$ was ranges from 6.5 to 15.9 nmol m$^{-2}$ s$^{-1}$.

![Figure 4.4](image)

**Figure 4.4** Ensemble mean diurnal variations in net ecosystem CH$_4$ exchange ($F_{\text{CH}_4}$), eddy CH$_4$ flux ($F_C$) and CH$_4$ storage change ($F_S$) from February 2014 to January 2017.
Figure 4.5 Ensemble mean diurnal variations friction velocity ($u^*$) from February 2014 to January 2017. Increased in turbulent mixing was started at 07:00.

4.3 Seasonal and inter-annual variations in $F_{\text{CH}_4}$

Mean of measured half-hourly $F_{\text{CH}_4}$ (± 1 SD) was $10.9 \pm 37.8$ nmol m$^{-2}$ s$^{-1}$, and thus the site was a net CH$_4$ source. On a monthly basis, gap-filled $F_{\text{CH}_4}$ was always positive (Fig. 4.1g). Seasonal variation in gap-filled $F_{\text{CH}_4}$ was almost similar with GWL and soil moisture (Figs. 4.1b and 4.1c). There was positive correlations between of $F_{\text{CH}_4}$ with GWL ($r = 0.58; P < 0.001$) and soil moisture ($r = 0.61; P < 0.001$). The peak $F_{\text{CH}_4}$ was 19.2 mg C m$^{-2}$ d$^{-1}$ in February 2015 when the GWL was above the soil surface. Annual $F_{\text{CH}_4}$ (mean monthly values) was much lower in February 2016–January 2017 (Fig. 4.3g).
4.4 Responses of $F_{CH4}$ to environmental variables

We examined the influences of GWL, soil moisture, $T_a$ and $T_s$ on $F_{CH4}$ by using linear or curvilinear regression. The relationships were examined by the procedure as described in section 3.4. Only GWL, soil moisture and $T_s$ show significant relationships with $F_{CH4}$, and were best-fitted with quadratic regressions ($P < 0.001$) (Fig. 4.6). The differences in $R^2$ between linear and curvilinear relationships were small within 0.0011 (Table 4.1). The GWL and soil moisture were positively associated with $F_{CH4}$. On contrary, the $T_s$ was negatively associated with $F_{CH4}$, which could be due to a negative correlation between soil temperature and GWL ($r = -0.35$, $P < 0.001$). The linear relationship between GWL and $F_{CH4}$ suggests that CH$_4$ emissions increase by 1.6 nmol m$^{-2}$ s$^{-1}$ for every 10 cm rise of GWL. By curvilinear relationship, the peak CH$_4$ emission was 12.4 nmol m$^{-2}$ s$^{-1}$ at GWL of 8 cm.

Figure 4.6 Responses of net ecosystem CH$_4$ exchange ($F_{CH4}$) to (a) groundwater level (GWL) and (b) soil moisture on a daily basis. The relationships were determined using measured data and regression curves were drawn.
Figure 4.6 (continued) Responses of net ecosystem CH₄ exchange (FₐCH₄) to (c) air temperature (Tₐ) and (d) soil temperature (Tₛ) on a daily basis. The relationships were determined using measured data and regression curves were drawn.

<table>
<thead>
<tr>
<th>Environmental variable</th>
<th>FₐCH₄ (nmol m⁻² s⁻¹)</th>
<th>Linear</th>
<th>Curvilinear</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWL (cm)</td>
<td>y = 0.16x + 13.4</td>
<td>y = -0.0023x² + 0.037x + 12.3</td>
<td>(R² = 0.0457)</td>
</tr>
<tr>
<td>Soil moisture (m³ m⁻³)</td>
<td>y = 13.1x + 2.2</td>
<td>y = -31.8x² + 50.6x - 7.8</td>
<td>(R² = 0.0613)</td>
</tr>
<tr>
<td>Tₛ (°C)</td>
<td>y = -3.0x + 76.7</td>
<td>y = 0.015x² - 3.7x + 84.6</td>
<td>(R² = 0.0786)</td>
</tr>
</tbody>
</table>
4.5 Annual CH$_4$ balance

Annual $F_{\text{CH}_4}$ (annual sum) for the annual periods of February 2014–January 2015, February 2015–January 2016 and February 2016–January 2017 were 4.35, 4.75 and 3.41 g C m$^{-2}$ yr$^{-1}$, respectively. The difference in annual $F_{\text{CH}_4}$ of the annual periods was within 1.5 g C m$^{-2}$ yr$^{-1}$. Mean annual $F_{\text{CH}_4}$ ($\pm$ 1 SD) was 4.17 $\pm$ 0.69 g C m$^{-2}$ yr$^{-1}$. 
Chapter 5

Methane balance of an oil palm plantation (OP)

5.1 Seasonal variations in environmental variables

In 2014, seasonal variation in monthly precipitation was anomalous (Fig. 5.1a) in which the monthly precipitation increased irregularly from February to December. The February 2014 was driest month over whole study period, with a monthly precipitation of 16.8 mm month\(^{-1}\). In 2015, the monthly precipitation was higher in the beginning and end of the year and relatively constant from February to August. In 2016, the monthly precipitation was higher in first half of the year. Figure 5.2a shows the ensemble mean of monthly precipitation for the common period of 3 years from February 2014 to January 2017. The seasonal variation in ensemble mean of OP is almost similar for the long term record (2005-2014) at local rainfall station near OP (Fig. 5.2b). The precipitation was higher in January or December. Annual precipitation was almost constant in all annual periods (Fig. 5.3a). Mean annual precipitation (± 1 SD) was 2507 ± 172 mm yr\(^{-1}\), which was comparable with the mean annual long-term precipitation (2005–2014) of 2797 ± 224 mm yr\(^{-1}\).

Seasonal variation in monthly GWL was relatively constant with no distinct seasonal pattern (Fig. 5.1b). Similar with UF and DF, the monthly GWL was positively correlated with monthly precipitation (\(r = 0.72; P < 0.001\)). The monthly GWL was ranged from –80 (March 2014) to –45 cm (January 2016). The effect of water management on GWL was apparent in this site, in which the GWL never rose above soil surface and its variation was narrowest.
among the three sites. Annual GWL showed an increasing trend during study period, ranged from −66 to −58 cm (Fig. 5.3b), and mean annual GWL (± 1 SD) was of −62 ± 4 cm.

Seasonal variation in soil moisture of the top 30-cm-thick layer was almost constant (Figs. 5.1c). The lowest monthly soil moisture was 0.29 m$^3$ m$^{-3}$ (October 2016) and never exceeds 0.54 m$^3$ m$^{-3}$ (January 2015) because of controlled GWL. Annual soil moisture showed a decreasing trend during study period, ranged from 0.43 to 0.46 m$^3$ m$^{-3}$ (Fig. 5.3c). Mean annual soil moisture (± 1 SD) was 0.42 ± 0.06 m$^3$ m$^{-3}$.

Seasonal variations in monthly $T_a$ and $T_s$ was narrow during study period in which $T_a$ was mostly higher than $T_s$ (Figs. 5.1d and 5.1e). Also, annual $T_a$ and $T_s$ varied narrowly within a range of 1.5°C (Fig 5.3d and 5.3e). Additionally, monthly solar radiation tended to be higher in July or August due to low precipitation (Fig. 5.1f). Annual solar radiation was ranged from 16.86 to 16.9 MJ m$^{-2}$ d$^{-1}$ (Fig. 5.3f).
Figure 5.1 Variations in monthly (a) precipitation, (b) groundwater level (GWL) and (c) soil moisture from February 2014 to January 2017. Vertical bars denote standard errors.
Figure 5.1 (continued) Variations in monthly (d) air temperature ($T_a$), (e) soil temperature ($T_s$), (f) solar radiation and (g) gap-filled daily net ecosystem CH$_4$ exchange ($F_{CH4}$) from February 2014 to January 2017. Vertical bars denote standard errors.
Figure 5.2 Ensemble mean seasonal variations in precipitation at (a) OP (3 years) and (b) local rainfall station near OP (10 years).
Figure 5.3 Variations in annual (a) precipitation (b) groundwater level (GWL), (c) soil moisture, (d) air temperature ($T_a$), (e) soil temperature ($T_s$), (f) solar radiation and (g) gap-filled daily net ecosystem CH$_4$ exchange ($F_{CH4}$) from February (Feb) 2014 to January (Jan) 2017.
5.2 Diurnal variations in CH$_4$ fluxes

The $F_{CH4}$ and $F_C$ were mostly positive and only $F_C$ showed a marked peak early in the morning at around 07:30-09:00 (Fig. 5.4) due to increase in turbulent mixing (Fig. 5.5). Increased in $F_C$ was lasted from 07:30 to 11:00 with a peak of 36.9 nmol m$^{-2}$ s$^{-1}$. Similar with UF and DF, CH$_4$ storage change was measured from a single point at above the oil palm canopy, which would has been underestimated. However, the morning flush of $F_C$ was compensated by decreased storage because there was no morning flush in $F_{CH4}$. There was no clear diurnal pattern in $F_{CH4}$, and the $F_{CH4}$ was much higher in the afternoon. The $F_{CH4}$ was ranges from $-7.5$ to $14$ nmol m$^{-2}$ s$^{-1}$.

![Figure 5.4](image.png)

**Figure 5.4** Ensemble mean diurnal variations in net ecosystem CH$_4$ exchange ($F_{CH4}$), eddy CH$_4$ flux ($F_C$) and CH$_4$ storage change ($F_S$) from February 2014 to January 2017.
Figure 5.5 Ensemble mean diurnal variations friction velocity ($u^*$) from February 2014 to January 2017. Increased in turbulent mixing was started at 07:00.

5.3 Seasonal and inter-annual variations in $F_{CH4}$

Mean of measured half-hourly $F_{CH4}$ ($\pm 1$ SD) was 5.8 $\pm$ 44.8 nmol m$^{-2}$ s$^{-1}$, and thus the site was a net CH$_4$ source. Unexpectedly, gap-filled $F_{CH4}$ was always positive on a monthly basis (Fig. 5.1g). Seasonal variation in gap-filled $F_{CH4}$ was differs from GWL and soil moisture (Fig. 5.1b and 5.1c). There was no significant correlations of $F_{CH4}$ with GWL ($r = 0.02; P > 0.1$) and soil moisture ($r = 0.27, P > 0.1$). The seasonal pattern of $F_{CH4}$ was generally consistent in all annual periods in which the $F_{CH4}$ increased from the beginning of the years to a peak and decreased towards the ending of the years. Annual $F_{CH4}$ (mean monthly values) increased slightly during study period (Fig. 5.3g).
5.4 Responses of $F_{\text{CH}_4}$ to environmental variables

Influences of GWL, soil moisture, $T_a$ and $T_s$ on $F_{\text{CH}_4}$ was examined using linear or curvilinear regression on a daily basis. The relationships were examined by the procedure as described in section 3.4. There was no significant relationship of $F_{\text{CH}_4}$ with GWL, soil moisture and $T_s$ on a daily basis (Fig. 5.6). However, the $F_{\text{CH}_4}$ was weakly associated with $T_a$ ($R^2 = 0.0111, P < 0.05$). Overall, the daily $F_{\text{CH}_4}$ were cluster around the zero horizontal line.

Figure 5.6 Responses of net ecosystem CH$_4$ exchange ($F_{\text{CH}_4}$) to (a) groundwater level (GWL), (b) soil moisture, (c) air temperature ($T_a$) and (d) soil temperature ($T_s$) on a daily basis. The relationships were determined using measured data and regression line was drawn.
5.5 Annual CH₄ balance

Annual \( F_{\text{CH}_4} \) (annual sum) were 1.96, 2.38 and 2.23 g C m\(^{-2}\) yr\(^{-1}\), respectively, for the annual periods of February 2014–January 2015, February 2015–January 2016 and February 2016–January 2017. The difference in annual \( F_{\text{CH}_4} \) among the annual period was within 0.42 g C m\(^{-2}\) yr\(^{-1}\). Mean annual \( F_{\text{CH}_4} \) (± 1 SD) was 2.19 ± 0.21 g C m\(^{-2}\) yr\(^{-1}\).
Chapter 6

Discussion

6.1 Environmental variables

Seasonal variations in monthly precipitations of all sites were not distinctly different from each other except in 2014 (Figs. 3.1a, 4.1a and 5.1a). On an annual basis, the UF and OP recorded the highest precipitation in February 15–January 16, whereas the DF recorded the highest precipitation in February 16-January 17 (Figs. 3.3a, 4.3a and 5.3a). However, the annual precipitation was not significantly different between the sites ($P > 0.05$, Fig. 6.1a). The difference in mean annual precipitations between the sites was within 90 mm only. In all sites, mean annual precipitation for the three years was lower than long-term mean annual precipitation (2005–2014), which was mainly due to an El Niño event of 2014–2016.

Seasonal variation in monthly GWL of DF was almost similar to UF except in 2014 (Figs. 3.1b and 4.1b). Because the GWL of DF was affected by water management of nearby oil palm plantations, and thus its GWL was mostly lower than UF. For oil palm cultivation, the GWL must be sufficiently low to avoid water stresses on oil palm trees as it can be detrimental for oil palm yield. As a result, the monthly GWL of OP was always far lower than the UF and DF (Figs 3.1b, 4.1b and 5.1b). There was a significant difference in GWL between the sites ($P < 0.001$; Fig. 6.1b). Mean annual GWL of UF was 4.2 and 12.7 times higher than DF and OP, respectively. In addition, the mean annual GWL of DF was 3 times higher than OP.
Monthly soil moisture of UF was mostly higher than DF except in 2014 (Figs. 3.1c and 4.1c). Because of high soil porosity at UF and DF (low density in Table 2.2), the variations in monthly soil moistures of UF and DF were much larger than OP. On an annual basis, the soil moisture was significantly different between the sites ($P < 0.05$; Fig. 6.1c). The highest annual soil moisture was recorded at UF followed by DF and OP. The soil moisture at UF was strongly controlled by the GWL ($r = 0.92; P < 0.001$). At DF, the soil moisture was also strongly by controlled by the GWL ($r = 0.77; P < 0.001$). However, at OP, the soil moisture was weakly regulated by the GWL ($r = 0.26; P < 0.001$). This indicates that the controlled GWL at OP may have reduced the influence of GWL on soil moisture.

The differences in mean annual $T_a$ and $T_s$ were within 1.1 and $2^\circ C$, respectively. The mean annual $T_a$ of UF and DF were significantly higher than OP ($P < 0.001$; Fig. 6.1d). This is probably due to different measurement heights of $T_a$, in which the $T_a$ were measured at 40 m at UF and DF and at 20 m at OP. The mean annual $T_s$ of UF and DF were significantly different from OP ($P < 0.01$; Fig. 6.1e). As shown in Table 2.2, both UF and DF had dense canopies (PAI $> 4 \text{ m}^2 \text{ m}^{-2}$; von Arx et al., 2013) and high tree density. The dense canopy and tree stems shield soil surfaces from solar radiation and reduce mixing of air below the canopy. In comparison, the OP had a sparse canopy (PAI $< 4 \text{ m}^2 \text{ m}^{-2}$) which allowed the solar radiation to reach the soil surface. Consequently, the $T_s$ of UF and DF were lower than OP. For solar radiation, there was no significant difference between the sites because all the sites are located in as close latitude range (Fig. 6.1f).
Figure 6.1 Spatial variations in mean annual (a) precipitation (b) groundwater level (GWL), (c) soil moisture, (d) air temperature ($T_a$), (e) soil temperature ($T_s$), (f) solar radiation and (g) gap-filled daily net ecosystem CH$_4$ exchange ($F_{CH4}$) from February 2014 to January 2017 at UF, DF and OP (3 years). Different letters at each site indicate statistically significant differences (Tukey’s test HSD, $P < 0.05$). Vertical bars denote standard errors.
6.2 Diurnal variations in CH$_4$ fluxes

In this study, we used above-canopy storage flux to calculate F$_{CH4}$, and unexpectedly a peak appeared in F$_{CH4}$ of UF (Fig. 3.4). A similar diurnal pattern of CH$_4$ flux with a morning flush was observed above the canopy of an Amazonia rainforest (Querino et al., 2011) in which the CH$_4$ flux was small but consistently showed venting peak in the early morning. The peak of F$_{CH4}$ is influenced by the canopy structure and CH$_4$ emission strength. At UF, the canopy height was 35 m, which was 10 and 27 m higher than the DF and OP, respectively. Thus, the volume space covered by the canopy at UF was much larger than DF and OP. Mean of measured half-hourly F$_{CH4}$ from UF was 20.7 ± 36.4 nmol m$^{-2}$ s$^{-1}$, which was 1.89 and 3.57 times higher than DF (10.9 ± 37.8 nmol m$^{-2}$ s$^{-1}$) and OP (5.8 ± 44.8 nmol m$^{-2}$ s$^{-1}$). With large canopy volume and high CH$_4$ emission at UF, a large volume of CH$_4$ was accumulated below the canopy of UF during nighttime. This caused the F$_S$ from open-path analyser insufficient to compensate the flush out of CH$_4$ during the onset of turbulence after sunrise. As a result an apparent peak only appeared in F$_{CH4}$ of UF. If the F$_C$ is well compensated by F$_S$, there would be no distinct diurnal pattern in F$_{CH4}$ as in DF (Fig. 4.4) and OP (Fig. 5.4). Thus, we hypothesise that the F$_{CH4}$ are mainly dominated by biological processes in the soil.

6.3 Effect of GWL on F$_{CH4}$

Due to different degree of disturbance, the GWL differed spatially across UF, DF and OP. Only in forest ecosystems of UF and DF, seasonal changes in F$_{CH4}$ were coincident with the rise and fall of GWL (Figs. 3.1b, 3.1g, 4.1b and 4.1g). Seasonal variations in GWL affect the CH$_4$ emissions by influencing zonation of methanogenesis and methanotrophy (Turetsky
et al., 2008; Munir and Strack, 2014). At UF and DF, high GWL were generally occurred at
the beginning and end of the years. During these periods, the high GWL increased saturated
layers of the soil, and restrict oxygen diffusion into soils. This condition allowed for larger
methanogenesis zone, fewer habitats for methanotrophy and thus a greater chance for CH₄
escape to the atmosphere. In contrast, a low GWL promote rapid oxygen diffusion into soil
which increase methanotrophy zone, and stimulate CH₄ oxidation (consumption). At UF and
DF; highest monthly CH₄ emissions were recorded when the GWL were above soil surfaces
whereby a greater proportion of soil pores were filled with water. When the GWL were above
soil surfaces, the monthly total CH₄ emissions were as high as 1.05 and 0.57 g C m⁻² month⁻¹,
respectively, for UF and DF. This suggests that a strictly anaerobic condition is required for
high CH₄ emissions in tropical peat. As shown in Figures 3.6a and 4.6a, the FₐH₄ were found
to be positively associated with GWL, consistent with previous studies conducted in tropical
peatland using the chamber technique (Furukawa et al., 2005; Inubushi et al., 2005). At OP,
the drainage on peatland has lowered the GWL to at least −45 cm continuously, and this has
removed the dependency of FₐH₄ on GWL (Fig. 5.6a). Some studies on middle latitude peat
ecosystems also have reported the influence of GWL on CH₄ emissions (Frenzel and
Karofeld, 2000; Munir and Strack, 2014; Olson et al., 2013; Song et al., 2015).

In addition, the changes in GWL may affect the amount of available substrates that
are required for methanogenesis. After GWL drawdown, increased aerobic degradation in
unsaturated layers consumes substrates that would promote CH₄ production in anoxic
conditions (Kettunen et al., 1999; Waddington and Day, 2007). Conversely, a high GWL
limits aerobic degradation, and thus the quantity and quality of substrate is much larger
(Waddington and Day, 2007). Obviously, the GWL at UF was the lowest in July-August
2014, whereas the lowest GWL at DF was in July-October 2015 (Figs. 3.1b and 4.1b). To
evaluate the effect of substrates on CH$_4$ emissions due to GWL changes, we calculated mean daily F$_{CH4}$ before and after lowest GWL periods (Table 6.1). The mean daily F$_{CH4}$ were calculated according to GWL ranges of –15 to 0 and –20 to –10 cm, respectively, for UF and DF. At UF, the mean daily F$_{CH4}$ before and after lowest GWL periods were 32.6 ± 8.04 and 10.5 ± 8.77 nmol m$^{-2}$ s$^{-1}$, respectively. Although the GWL was in the same ranges for two periods, the mean daily F$_{CH4}$ before lowest GWL period was 3.1 times higher than after lowest GWL period. This indicates that available substrate for CH$_4$ production before lowest GWL period could be higher than after lowest GWL period. The mean daily F$_{CH4}$ was significantly (P < 0.01) different before and after lowest GWL periods. Similar differences were also found at DF in which the mean daily F$_{CH4}$ before and after lowest GWL periods were 12.6 ± 7.76 and 4.17 ± 4.43 nmol m$^{-2}$ s$^{-1}$, respectively. Thus, we hypothesize that dry period can lead to higher degradation of substrate, resulting in lack of substrate for CH$_4$ production when the GWL increase again. Relatively large scattering in Figures 3.6a and 4.6a was probably attributed to this hysteresis in the relationship between F$_{CH4}$ and GWL. Additionally, the large scattered F$_{CH4}$ 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 F$_{CH4}$.

Conversion of peat swamp forests to oil palm plantations require lowering GWL which is especially important to prevent shallow rooting and leaning of oil palm trees. The GWL drawdown by drainage increased oxygen diffusion into peats, results in drier surface peats and enhanced methanotrophic activity. A study reported that drainage led to a significant decrease in CH$_4$ emissions, potential CH$_4$ production, and the abundance and diversity of methanogens as compared to pristine peatlands (Urbanová et al., 2013).
(Jauhiainen et al., 2008) reported that dry tropical peat surface due to drainage had a neutral or negative CH$_4$ balance.

Table 6.1 Mean (± 1SD) daily F$_{CH_4}$ of UF and DF before and after lowest GWL periods in 2014 and 2015, respectively. Two GWL ranges of –15 to 0 cm and –20 to –10 cm were used for UF and DF, respectively. Different letters indicate statistically significant differences between the periods in each site (Welch’s t-test, $P < 0.01$).

<table>
<thead>
<tr>
<th>Site</th>
<th>Period</th>
<th>Number of days</th>
<th>GWL (cm)</th>
<th>Mean F$_{CH_4}$ (nmol m$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UF</td>
<td>June 2014 (before)</td>
<td>13</td>
<td>–15 to 0</td>
<td>32.6 ± 8.04$^a$</td>
</tr>
<tr>
<td></td>
<td>September 2014 (after)</td>
<td>17</td>
<td>–15 to 0</td>
<td>10.5 ± 8.77$^b$</td>
</tr>
<tr>
<td>DF</td>
<td>May-June 2015 (before)</td>
<td>42</td>
<td>–20 to –10</td>
<td>12.6 ± 7.76$^a$</td>
</tr>
<tr>
<td></td>
<td>November-December 2015 (after)</td>
<td>6</td>
<td>–20 to –10</td>
<td>4.17 ± 4.43$^b$</td>
</tr>
</tbody>
</table>

6.4 Effect of soil moistures, air temperatures ($T_a$) and soil temperatures ($T_s$) on F$_{CH_4}$

At UF and DF, the soil moistures were strongly regulated by GWL ($r = 0.77$ and 0.92), and this water-related factor are important in controlling CH$_4$ emission from tropical peat swamp forests. At both sites, the soil moistures showed positive associations with F$_{CH_4}$ (Figs 3.6b and 4.6b). Increased soil moisture stimulates soil anoxia and subsequent methanogenesis that may diminish net CH$_4$ consumption (Sexstone and Mains, 1990; Yavitt et al., 1995; McLain and Ahmann, 2008). At OP, the controlled GWL has led to constant variation in soil.
moisture (Figs. 5.1b and 5.1c), and this may have removed the influence of soil moisture on $F_{CH_4}$ (Fig. 5.6b).

In middle- and high-latitude zones, seasonal variations in temperatures are well pronounced, with cold winters and short summers. In tropical zone, seasonal variation in temperature is far less pronounced than middle- and high-latitude zones, and temperatures is maintained at a near optimal or at optimal which is ideal for efficient gas formation throughout the year (Jauhiainen et al., 2005; Villa and Mitsch, 2014). The $T_a$ showed significant relationships with $F_{CH_4}$ at UF and OP, whereas no significant relationship was found at DF. The possible reason for these relationships may be attributable to natural spatiality of $F_{CH_4}$. Soil CH$_4$ production is a microbiological process depends on temperature (Dunfield et al., 1993). In general, there is a positive relationship between $T_s$ and CH$_4$ flux in middle- and high-latitude peatlands (Jackowicz-Koreczyński et al., 2010; Schrier-Uijl et al., 2010; Hanis et al., 2013; Olson et al., 2013; Song et al., 2015). In this study, however, $F_{CH_4}$ was negatively associated with $T_s$ at UF and DF, and no significant relationship was found at OP. The negative association between $T_s$ and $F_{CH_4}$ should be unreal because both $T_s$ and $F_{CH_4}$ was controlled by GWL. Increase in GWL will increase the $F_{CH_4}$, but decrease the $T_s$.

6.5 Inter-site comparison of CH$_4$ fluxes

There was a significant difference in annual $F_{CH_4}$ among the sites ($P < 0.001$; Fig. 6.1f). The mean annual $F_{CH_4}$ (8.46 ± 0.51 g C m$^{-2}$ yr$^{-1}$) of UF doubled that of DF (4.17 ± 0.69 g C m$^{-2}$ yr$^{-1}$) and was about four times higher than that of OP (2.19 ± 0.21 g C m$^{-2}$ yr$^{-1}$). In addition, annual $F_C$ without $u^*$ correction were 8.48 ± 0.30, 4.59 ± 0.50 and 2.96 ± 0.29 g C m$^{-2}$ yr$^{-1}$, respectively, for UF, DF and OP. Annual accumulations of $F_{CH_4}$ and $F_C$ could be
equivalent, because positive and negative values of CH₄ storage change were compensated each other. Similarly with Fₐ CH₄, the annual eddy CH₄ was significantly different among the sites (P < 0.001). The similar annual CH₄ balances obtained independently of u* correction indicate that these tropical peat ecosystems functioned as a net CH₄ source, respectively.

Annual CH₄ emission was largest in UF, followed by DF and OP. To examine the difference among sites, gap-filled Fₐ CH₄ was plotted against GWL on a monthly or an annual basis (Fig. 6.2), including all data from the three sites. A significant exponential relationship was found both on a monthly (P < 0.001; R² = 0.76) or an annual (P < 0.001; R² = 0.88) basis. Monthly mean Fₐ CH₄ increased sharply when monthly mean GWL was above −20 cm, and the relationship suggests that Fₐ CH₄ was more than 20 mg C m⁻² d⁻¹ in Sarawak’s peat swamp forest when the ground is flooded. On an annual basis, annual Fₐ CH₄ might be 8.03 g C m⁻² yr⁻¹ if annual mean GWL was zero. A similar exponential relationship was reported for annual data of CH₄ flux and GWL from northern peatlands (Abdalla et al., 2016). The significant relationship indicates that the difference in Fₐ CH₄ among the three sites was mainly due to the difference in GWL. Because the GWL of OP was far below the soil surface, the annual CH₄ emission of OP was the lowest out of all sites. Also, the equations would be applicable to estimate CH₄ emissions from peatlands in Sarawak using GWL on a monthly or annual time scale.

Aerobic zones caused by the difference in GWL heights induced different oxidation potentials across the sites. These aerobic zones act as diffusion barrier for the transport CH₄ to atmosphere. Mean annual GWL of DF was 4.2 times lower than UF. Under lower GWL condition, CH₄ production would have been suppressed while CH₄ oxidation would have been simulated. Consequently, higher oxidation rate (negative flux) was observed at DF. Around 13% of daily Fₐ CH₄ of DF was negative which was much higher than UF with only
3.2 % negative daily $F_{\text{CH}_4}$ (Table 6.4). There was 27.4 % negative daily $F_{\text{CH}_4}$ at OP, and it was much higher than UF and DF.

Figure 6.2 Relationships between gap-filled net ecosystem $\text{CH}_4$ exchange ($F_{\text{CH}_4}$) and groundwater level (GWL) on (a) monthly basis and (b) annual bases. An exponential curve was significantly fitted.
Table 6.4 Positive and negative daily FCH$_4$ of UF, DF and OP. Numbers in parentheses indicate the percentages of the data.

<table>
<thead>
<tr>
<th>Site</th>
<th>Positive FCH$_4$ (nmol m$^{-2}$ s$^{-1}$)</th>
<th>Negative FCH$_4$ (nmol m$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UF</td>
<td>0.10–66.4 (96.8%)</td>
<td>0.10–14.3 (3.2%)</td>
</tr>
<tr>
<td>DF</td>
<td>0.02–61.0 (86.9%)</td>
<td>0.38–43.9 (13.1%)</td>
</tr>
<tr>
<td>OP</td>
<td>0.09–44.3 (72.6%)</td>
<td>0.07–57.4 (27.4%)</td>
</tr>
</tbody>
</table>

6.6 Comparison with other studies on tropical peat ecosystems

In tropical peatlands, soil CH$_4$ flux has been measured by static chambers. This study shows the first ecosystem-scale CH$_4$ fluxes from three different peat ecosystems measured by the eddy covariance technique. Table 6.2 shows various published findings of annual CH$_4$ emissions that were studied with soil static chamber, field incubation experiment and eddy covariance from tropical peatlands.

Previous study on UF reported that the annual F$_{CH4}$ was 7.5–10.8 g C m$^{-2}$ yr$^{-1}$ from March 2014 to February 2015 (Wong et al., 2018) (Table 6.2). In this study, the annual F$_{CH4}$ of UF (February 2014–January 2017) was 7.89–8.87 g C m$^{-2}$ yr$^{-1}$ which was within the reported range. However, the annual F$_{CH4}$ of UF was much higher than annual soil CH$_4$ emissions reported by previous chamber and incubation studies from tropical peatlands (Inubushi et al., 2003; Hadi et al., 2005; Jauhiainen et al., 2005; 2008; Melling et al., 2005b; Sangok et al., 2017), with a largest difference of 9.15 g C m$^{-2}$ yr$^{-1}$.  

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Annual $F_{\text{CH}_4}$ from DF was 3.41–4.35 g C m$^{-2}$ yr$^{-1}$ which was lower than (Wong et al., 2018) (Table 6.2). The annual $F_{\text{CH}_4}$ was in between 1.02 and 4.4 g C m$^{-2}$ yr$^{-1}$ from the ecosystems of secondary and logged over forests (Inubushi et al., 2003; Hadi et al., 2005; Jauhiainen et al., 2005). However, the annual $F_{\text{CH}_4}$ was much higher than some of the annual soil CH$_4$ emissions (Melling et al., 2005b; Jauhiainen et al., 2008; Sangok et al., 2017).

Annual soil CH$_4$ balance from oil palm plantation (Melling et al., 2005b) and drainage-affected selectively logged forest (Jauhiainen et al., 2005) were small CH$_4$ sinks (–0.28 to –0.16 C m$^{-2}$ yr$^{-1}$) (Table 6.2). However, in our study, the annual $F_{\text{CH}_4}$ of OP (oil palm plantation) was a small CH$_4$ source of 1.96–2.38 g C m$^{-2}$ yr$^{-1}$. The value was close to the annual soil CH$_4$ emissions (1.02–1.2 g C m$^{-2}$ yr$^{-1}$) from secondary and logged over forests (Inubushi et al., 2003; Jauhiainen et al., 2005).
<table>
<thead>
<tr>
<th>Climate</th>
<th>Location</th>
<th>Technique</th>
<th>Ecosystem</th>
<th>CH$_4$ emission (g C m$^{-2}$ yr$^{-1}$)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical</td>
<td>Sarawak, Malaysia</td>
<td>Eddy covariance</td>
<td>UF *</td>
<td>7.89 to 8.87</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DF *</td>
<td>3.41 to 4.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OP °</td>
<td>1.96 to 2.38</td>
<td></td>
</tr>
<tr>
<td>Tropical</td>
<td>Sarawak, Malaysia</td>
<td>Eddy covariance</td>
<td>UF *</td>
<td>7.5 to 10.8</td>
<td>Wong et al. (2018)</td>
</tr>
<tr>
<td>Tropical</td>
<td>South Kalimantan, Indonesia</td>
<td>Soil static chamber</td>
<td>Secondary forest</td>
<td>1.2</td>
<td>Inubushi et al. (2003)</td>
</tr>
<tr>
<td>Tropical</td>
<td>South Kalimantan, Indonesia</td>
<td>Soil static chamber</td>
<td>Secondary forest</td>
<td>4.4</td>
<td>Hadi et al. (2005)</td>
</tr>
<tr>
<td>Tropical</td>
<td>Sarawak, Malaysia</td>
<td>Soil static chamber</td>
<td>Mixed peat swamp forest</td>
<td>0.018</td>
<td>Melling et al. (2005b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Oil palm plantation °</td>
<td>−0.015</td>
<td></td>
</tr>
<tr>
<td>Tropical</td>
<td>Central Kalimantan, Indonesia</td>
<td>Soil static chamber</td>
<td>Logged over forest</td>
<td>&lt; 1.02</td>
<td>Jauhiainen et al. (2005)</td>
</tr>
<tr>
<td>Tropical</td>
<td>Central Kalimantan, Indonesia</td>
<td>Soil static chamber</td>
<td>Deforested area °</td>
<td>0.148 to 0.205</td>
<td>Jauhiainen et al. (2008)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Drainage-affected selectively logged forest °</td>
<td>−0.28 to −0.16</td>
<td></td>
</tr>
<tr>
<td>Tropical</td>
<td>Sarawak, Malaysia</td>
<td>Field incubation</td>
<td>Peat samples from Mixed peat swamp, Alan Batu and Alan Bunga forests (in an oil palm plantation °)</td>
<td>0.113 to 0.253</td>
<td>Sangok et al. (2017)</td>
</tr>
</tbody>
</table>

* Undrained peat ecosystem.

° Drained peat ecosystem.
6.7 Comparison with other studies on middle- and high-latitude peat ecosystems

Published annual CH$_4$ emissions from tropical peat ecosystems (Tables 6.2) are quite variable and often lower than those of mid- and high-latitude peat ecosystems measured by the eddy covariance technique (Table 6.3). Mean annual CH$_4$ emission of all listed mid- and high-latitude peat ecosystems is 12.9 ± 7.3 g C m$^{-2}$ yr$^{-1}$ (Hargreaves et al., 2001; Rinne et al., 2007; Jackowicz-Korezyński et al., 2010; Schrier-Uijl et al., 2010; Tagesson et al., 2012; Hanis et al., 2013; Olson et al., 2013; Song et al., 2015; Fortuniak et al., 2017). In comparison, the annual F$_{CH4}$ of UF, DF and OP were lower than the overall mean annual CH$_4$ emission. However, the annual F$_{CH4}$ of UF was comparable with annual CH$_4$ emission of subarctic oligotrophic fen (Rinne et al., 2007), and was higher than those of subartic fens (Hargreaves et al., 2001; Hanis et al., 2013) and an arctic fen (Tagesson et al., 2012). In addition, the annual F$_{CH4}$ of DF was comparable to the values reported by Hargreaves et al. (2001) and Hanis et al. (2013). Thus, the comparisons indicate that the tropical peat swamp forests are modest CH$_4$ sources to the atmosphere despite woody peats. In tropical peat swamp forests, the poor quality of woody peat with much lignin in ombrotrophic conditions restrict CH$_4$ production (Jauhiainen et al., 2016), and effective CH$_4$ oxidation at surface layer likely reduce the CH$_4$ emissions from tropical peatland (Wright et al., 2011). Furthermore, oxygen supply through the plant roots can reduce CH$_4$ production even under flooded conditions (Adji et al., 2014).
Table 6.3 Comparison of annual CH$_4$ emissions with previous studies on middle- and high-latitudes peatlands.

<table>
<thead>
<tr>
<th>Climate</th>
<th>Location</th>
<th>Technique</th>
<th>Ecosystem</th>
<th>CH$_4$ emission (g C m$^{-2}$ yr$^{-1}$)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical</td>
<td>Sarawak, Malaysia</td>
<td>Eddy covariance</td>
<td>UF $^*$</td>
<td>7.89 to 8.87</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DF $^*$</td>
<td>3.41 to 4.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OP $^\circ$</td>
<td>1.96 to 2.38</td>
<td></td>
</tr>
<tr>
<td>Temperate</td>
<td>Minnesota, USA</td>
<td>Eddy covariance</td>
<td>Poor fen</td>
<td>16.3*</td>
<td>Olson et al. (2013)</td>
</tr>
<tr>
<td>Temperate</td>
<td>Qinghai plateau, China</td>
<td>Eddy covariance</td>
<td>Alpine peatland (silty clay loam)</td>
<td>22.6*</td>
<td>Song et al. (2015)</td>
</tr>
<tr>
<td>Temperate</td>
<td>Biebrza, Poland</td>
<td>Eddy covariance</td>
<td>River valley fen</td>
<td>18.4*</td>
<td>Fortuniak et al. (2017)</td>
</tr>
<tr>
<td>Subarctic</td>
<td>Kaamanen, Finland</td>
<td>Eddy covariance</td>
<td>Aapa mire (fen)</td>
<td>4.1</td>
<td>Hargreaves et al. (2001)</td>
</tr>
<tr>
<td>Subarctic</td>
<td>Ruovesi, Finland</td>
<td>Eddy covariance</td>
<td>Oligotrophic fen</td>
<td>9.4</td>
<td>Rinne et al. (2007)</td>
</tr>
<tr>
<td>Subarctic</td>
<td>Stordalen, Sweden</td>
<td>Eddy covariance</td>
<td>Mosaic of ombrotrophic and minerotrophic peatlands</td>
<td>20.2*</td>
<td>Jackowicz-Korczyński et al. (2010)</td>
</tr>
<tr>
<td>Subarctic</td>
<td>Manitoba, Canada</td>
<td>Eddy covariance</td>
<td>Eutrophic fen</td>
<td>5.1$^\dagger$</td>
<td>Hanis et al. (2013)</td>
</tr>
<tr>
<td>Arctic</td>
<td>Zackenberg, Greenland</td>
<td>Eddy covariance</td>
<td>Fen</td>
<td>7.1*</td>
<td>Tagesson et al. (2012)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mean ± 1 SD 12.9 ± 7.3</td>
<td></td>
</tr>
</tbody>
</table>

$^*$ Undrained peat ecosystem.

$^\circ$ Drained peat ecosystem.

$^*$ Mean of different annual periods.

$^\dagger$ Mean of three gap-filling techniques.
6.8 CH₄ emission sources

Annual FₐCH₄ measured by the eddy covariance technique were much larger than the annual soil CH₄ emissions from tropical peatlands (Table 6.2) mainly because the annual FₐCH₄ integrate various CH₄ fluxes that were unable captured by soil static chamber. These CH₄ fluxes can be from/to hollow or hummock areas, tree stems, ditches, etc.

It is difficult to determine a spatially-representative soil CH₄ flux by the chamber technique because of uneven microtopography and complex water conditions. For example, soil CH₄ emissions are higher from hollows than hummocks (Pangala et al., 2013). In UF and DF, there are many hollow and hummock areas. Some of the hollow areas were water-filled even in the dry period, especially in UF. Gap-filled FₐCH₄ in the driest months of UF (July 2014) and DF (June 2014) contributed 7% and 6.5%, respectively, to annual FₐCH₄ of 2014. These hollow areas could be hot spots of CH₄ emissions.

It is known that net emission rates of CH₄ are greatly influenced by the transport of CH₄ through herbaceous plants in boreal and temperate peatlands (Waddington et al., 1996; Ding et al., 2003; Frenzel and Karofeld, 2000). Also, tree species growing on waterlogged soils transfer CH₄ produced in the soil and emit the CH₄ from their stems to the atmosphere (Terazawa et al., 2007; Gauci et al., 2010; Rice et al., 2010; Pangala et al., 2013; 2015; 2017). With root systems penetrating anoxic soil horizons, plants transport CH₄ 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 Central Kalimantan of Indonesia, CH₄ emission from tree stems was greater than soil surfaces, accounting for 62–87% of total ecosystem CH₄ efflux from a
relatively undisturbed tropical peat swamp forest (Pangala et al., 2013). In their study, one of the dominant tree species emitting CH$_4$ is *Shorea balangeran*. The UF and DF are dominated by *Shorea albida* which is classified into the same species as *Shorea balangeran*. Thus, *Shorea Albida* probably has contributed significantly to the annual CH$_4$ emission of UF and DF. A recent study in Amazon floodplain has shown that the escape soil gas through wetland tree stems is the dominant source of CH$_4$ emissions (Pangala et al., 2017). They showed that the CH$_4$ effluxes from Amazonian tree stems were up to 200 times larger than emissions of the tropical peat swamp forest in Indonesia (Pangala et al., 2013; 2017). It may be possible that emissions via tree stems are proportionally more significant than overall CH$_4$ emission during low GWL period when CH$_4$ oxidation can be high if soil surface exposed to air. Moreover, (Wang et al., 2016) inferred that CH$_4$ emitted from tree stems on wet soils was partly derived from CH$_4$ produced in wet heartwood.

In drained peatland ecosystems, the CH$_4$ fluxes from soil surfaces tend to be near zero or sink (Roulet et al., 1993; Martikainen et al., 1995; Flessa et al., 1998; Melling et al., 2005b; von Arnold et al., 2005; Jauhiainen et al, 2008; Ojanen et al., 2010). Despite drainage on peatland can alters soil characteristics and reduces soil CH$_4$ flux on a meter square basis, ditches within drained sites can serve as important sources of CH$_4$ (Turetsky et al., 2014; Minkkinen and Laine, 2006; Hendriks et al., 2007; Teh et al., 2011; Hyvönen et al., 2013). We speculate that the CH$_4$ emission in OP may be due to the emissions from ditches, which were constantly covered with water. Large CH$_4$ emission can emitted from ditch if CH$_4$ rich water from the surrounding peat seep into the ditch and are degassed (Turetsky et al., 2014). Teh et al. (2011) reported that the ditches occupy only 5% of the land area but they accounted more than 84% of CH$_4$ emissions. In Central Kalimantan of Indonesia, the CH$_4$ from settled canal contributed 31% to the total cumulative equivalent annual emission (Jauhiainen and
Silvennoinen, 2012). Emissions from ditches may have a great impact on the total CH₄ emissions from drained peatlands (Minkkinen and Laine, 2006). At OP, the areal ratio of fetch (diameter of 1 km) and ditches within the fetch was 41:1. Although the ditches occupy only a small fraction of the landscape of oil palm plantation, the positive ecosystem-scale annual CH₄ emission observed here suggest that ditches in oil palm plantation must be considered when calculating carbon balances, especially for studies using static chamber technique. If the speculation is valid, a large spatial variability can be found in CH₄ fluxes between soil surface and ditches in drained tropical peat ecosystems.

6.9 Global warming potential

We assessed the global warming potential (GWP) of DF based on CO₂ and CH₄ for DF. Kiew et al. (2018) reported the annual CO₂ balance of DF from four-year-long eddy flux measurement until 2014. According to their study, DF was a net CO₂ sink of 136 g C m⁻² yr⁻¹. The annual F₇H₄ of 4.19 g C m⁻² yr⁻¹ can be converted into CO₂ equivalents of 157 g CO₂e m⁻² yr⁻¹ (43 g C CO₂ m⁻² yr⁻¹) using a GWP factor of 28 (IPCC, 2013). This scaling factor represents the global warming potential for CH₄ over a 100-year time horizon. Thus, the net GWP (CO₂ equivalents) was calculated to be −93 g C m⁻² yr⁻¹ as the sum of −136 (CO₂) and 43 (CH₄) g C m⁻² yr⁻¹. Consequently, the CH₄ emission decreased the CO₂ sequestration by 32%.

6.10 Effect of land conversion on CH₄ balance

Atmospheric concentration of CH₄ has increased greatly by 150% since pre-industrial era, rising from 722 ppb in 1750 to 1803 ppb in 2011 (IPCC, 2013). Zhang et al. (2017)
estimated that despite decreasing wetland extent and increased drought frequency in tropics, tropical wetlands remain the world’s largest natural source responsible for $\sim53.2 \pm 0.7\%$ of CH$_4$ emissions by the end of the 21st century under representative concentration pathway 8.5. The contribution of tropical peat ecosystems to the global CH$_4$ budget cannot be neglected because the annual CH$_4$ emissions were as high as 2.23–8.46 g C m$^{-2}$ yr$^{-1}$ as measured in this study. Moreover, the tropical peatland accounted for more than 11% of global peatland area (Page et al., 2011; Dargie et al., 2017). Under drained soil conditions, organic matter decomposition in tropical peatlands is accelerated which in turn increases the rate of CO$_2$ emissions to the atmosphere (Jauhiainen et al., 2008; Hirano et al., 2012; Itoh et al., 2017), whereas the CH$_4$ emissions are greatly reduced. The CH$_4$ balances displayed exponential responses to GWL changes across three sites (Fig. 6.2) indicating decreased emissions with land conversion. Here, we suggest that conversion of a natural tropical peat swamp forest to an oil palm plantation would reduce the CH$_4$ emissions by more than 70%, whereas the reduction from conversion of secondary tropical peats swamp forest would be more than 40%.
Chapter 7

Conclusions and Recommendations

7.1 Conclusions

Tropical peatlands represent a globally important carbon reservoir, storing an enormous amount of soil organic carbon (88.6 Gt), with substantial portion being in Southeast Asia. To date, data concerning tropical peat CH₄ fluxes are limited. They are based on only a few measurements from short-term studies by soil static chamber which would be insufficient to assess CH₄ flux from a whole ecosystem. This is because the static chamber only consider soil CH₄ flux but not whole-ecosystem CH₄ flux, and with insufficient replicates to cover heterogeneity of tropical peat. In recent decades, Southeast Asian peatlands have experienced rapid land cover changes, and lowering GWL by drainage for monoculture cultivation. Majority of the studies have focused on CO₂ balance and the effects on CH₄ balance remains uncertain.

In this study, we measured CH₄ fluxes from three different peat ecosystems in Sarawak, Malaysia during a period of three years from February 2014 to January 2017. The three peat ecosystems were representing different degree of disturbance, namely an undrained peat swamp forest (UF), a relatively disturbed peat swamp forest (DF) and an oil palm plantation (OP). Our objectives were to quantify the $F_{CH_4}$; examine the diurnal and seasonal variations of $F_{CH_4}$; determine the response of $F_{CH_4}$ to GWL; comparison of CH₄ flux among
three ecosystems and discuss inter-site difference. We measured the CH$_4$ flux at above the canopy of each ecosystem using the eddy covariance technique with open-path CH$_4$ analyser. Although some data were missing due to technical problems of eddy covariance system, the data sets obtained were able to provide unique insight for the CH$_4$ emissions.

Between the ecosystems, annual precipitation was not differed significantly. However, the precipitation-related factor, that is, GWL was differed greatly across the ecosystems due to different degree of disturbance. The mean annual GWL (± 1 SD) was the highest at the UF (−4.9 ± 2.6 cm) followed by the DF (−20.8 ± 2.2 cm) and OP (−62 ± 4 cm). To our knowledge, there is still no study comparing the CH$_4$ balances of tropical peat ecosystems using the eddy covariance technique. Here, the findings of this study can be summarized as follows:

- All ecosystems were net source of CH$_4$ even in the drained ecosystem of oil palm plantation. Mean half-hourly measured F$_{\text{CH}_4}$ (± 1 SD) from February 2014 to January 2017 for UF, DF and OP were 20.7 ± 36.4, 10.9 ± 37.8 and 5.8 ± 44.8 nmol m$^{-2}$ s$^{-1}$, respectively.
- All ecosystems showed morning flushes of CH$_4$, and an apparent peak in F$_{\text{CH}_4}$ was observed at UF.
- At UF and DF, the F$_{\text{CH}_4}$ varied seasonally in relation to GWL with the highest value in the rainy season, when GWL rose aboveground. Even in the driest month, when GWL were averaged at −30 cm (UF) or −50.6 cm (DF), the swamp forests were remained as a CH$_4$ source.
- On a daily basis, the F$_{\text{CH}_4}$ was positively associated with GWL in UF and DF.
- The F$_{\text{CH}_4}$ of OP did not varied according to GWL and no significant relationship was found between them. This was attributable to the controlled GWL in between −80 cm and −45 cm by the plantation.
• Mean annual $F_{\text{CH}_4}$ of UF, DF and OP were $8.46 \pm 0.51$, $4.17 \pm 0.69$ and $2.19 \pm 0.21$ g C m$^{-2}$ yr$^{-1}$.

• All annual CH$_4$ emissions were much higher 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 and ditches which were not covered by the previous studies.

• Overall, the annual 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.

• Annual $F_{\text{CH}_4}$ was significantly different between the ecosystems. The $F_{\text{CH}_4}$ displayed exponential responses to GWL changes across UF, DF and OP indicating decreased CH$_4$ emissions with land conversion.

7.2 **Recommendations**

• Different types of tropical peat swamp forest are distributed in zonation on a peat dome. Therefore, to evaluate the contribution of CH$_4$ emission from tropical peat swamp forest to global CH$_4$ cycles, further studies are necessary to measure $F_{\text{CH}_4}$ separately in each forest type.

• Tree stems CH$_4$ emission is an important source of CH$_4$ and further study is required to identify the CH$_4$-emitting tree stem in tropical peat swamp forests of Sarawak.

• Seasonal changes in GWL could affect the substrate availability for CH$_4$ production, and further studies of the degradation of substrate due to GWL changes are required.

• Ditches in oil palm plantations could be an important source of CH$_4$, and further researches on the CH$_4$ emissions from the ditches in an oil palm plantation is needed.
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Acknowledgments

First and foremost, I wish to take this opportunity to express my sincere gratitude to my advisor, Prof. Dr. Takashi Hirano for the continuous support of my PhD study and related research, for his patience and immense knowledge. His scientific inputs, personal helps and friendly nature has always made me feel at ease with him and I could always look back on him for any support during my course of PhD.

I would also like to acknowledge and deepest appreciation to Dr. Ryuichi Hirata for his valuable comments and generous assistance toward the completion of this PhD dissertation. His expert guidance, perfect supervision and valuable suggestions at each and every stage of the research work have helped me in all the time of research. I could not have imagined having a better advisor and mentor for my PhD study.

Special thanks to Dr. Lulie, for her meticulous suggestions and astute criticism throughout my study. I am grateful to have a patient, attentive and motivation director to help me in completing PhD. Without her precious support, this thesis would not have been possible and I shall eternally be grateful to her, for giving me the opportunity to undertake this research study and to persevere and complete it satisfactorily.

I would also like to extend my deepest appreciation to Prof. Dr. Ryusuke Hatano, Prof. Dr. Ryoji Samesima and Dr. Hiroyuki Yamada, who have taught me a lot and shared their valuable knowledge. They have offered much advice and insight throughout my work.

It is my pleasure to express deep gratitude to Sarawak State Government and Malaysian Palm Oil Board. Special thanks to supporting staff of Sarawak Tropical Peat Research Institute for their support in fieldwork and site management. I acknowledge Malaysian Meteorological Department (Sarawak branch) and Department of Irrigation and Drainage, Sarawak for sharing the meteorological data. I humbly give my gratitude to the Government of Japan through the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) for the scholarship (MONBUKAGAKUSHO) that enabled me to pursue a field research for my dissertation, to further improve my knowledge of ecosystem methane exchanges.

My heartfelt thanks to my fellow labmates, for always being there and bearing with me the good and bad times during my wonderful days in Japan. I had a great time at the Laboratory of Environmental Informatics or Laboratory of Ecological and Environmental Physics, Graduate School of Agriculture, Hokkaido University.

Last but not least, I would like to convey my gratitude to my beloved parents and wife for their support and spiritual encouragement at all the time during my studies in Hokkaido University. I will be forever grateful for your love.