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Methane balance of tropical peat ecosystems in Sarawak, Malaysia

(マレーシア·サラワク州における熱帯泥炭生態系のメタン収支)

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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_{CH4} was determined half-hourly as the sum of eddy CH_4 flux and CH_4 storage change and summed up annually after gap filling. Daily mean F_{CH4} was positively correlated to GWL in UF and DF, in which GWL governed the production and oxidation of CH_4 in peat. On the other hand, F_{CH4} was almost independent of GWL in OP, in which GWL was lowered by drainage. Monthly mean F_{CH4} was always positive even in drained OP, meaning CH_4 sources. Mean annual 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 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 CH_4 emission from UF was lower than those from mid-latitude peat ecosystems, though it was much higher than soil CH_4 emissions measured by the chamber technique in tropical peat swamp forests. The difference was probably due to CH_4 emissions from tree stems, which were not measured in the soil chamber studies.

A significant positive relationship was found between F_{CH4} 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 CH_4 emissions, because the land conversion accompanies drainage. However, the decrease of 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 CH_4 source probably because of high CH_4 emissions from ditches.

Contents

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 (Dommain 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; Dommain 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).

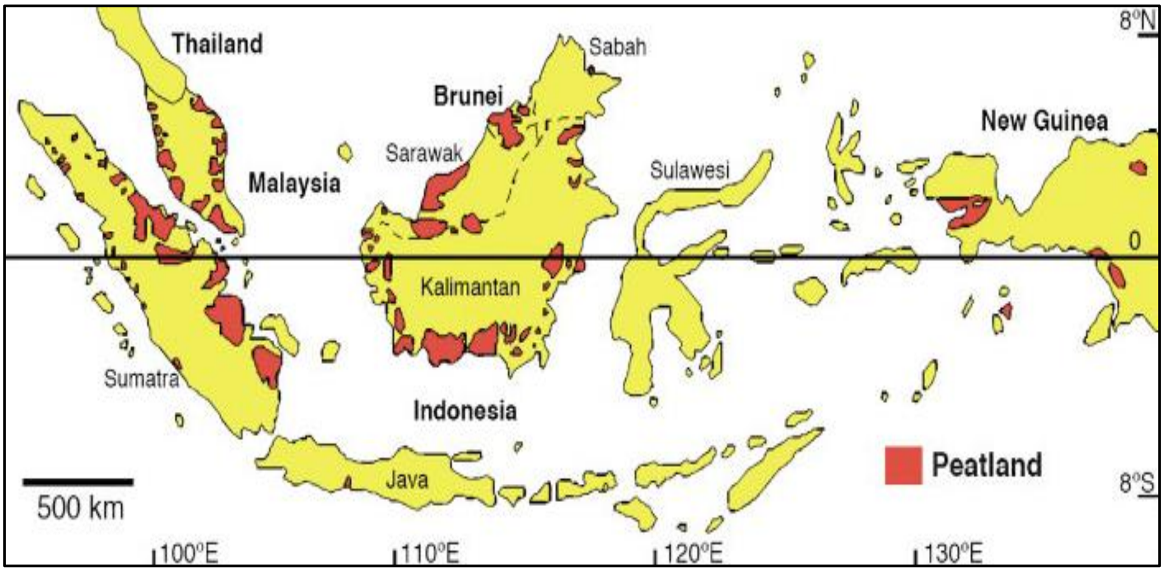


Figure 1.1 Distribution of the peatlands in Southeast Asia (Wösten et al., 2008).

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 Selunsor 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 emision 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, CH_4 flux showed a large spatial variation in horizontal and vertical directions. Microtopography on the forest floor consisting of hummocks and hollows causes the horizontal variation, because soil CH_4 efflux is higher on hollows (Pangala et al., 2015). Also, Pangala et al. (2013) reported that dominant trees in tropical peat swamp forest in Indonesia emitted a considerable amount of CH_4 from their stems. Furthermore, there are CH_4-emitting termites nesting above the ground of tropical peat swamp forests (Fraser et al., 1986; Martius et al., 1993; Jeeva et al., 1999; Vaessen et al., 2011). Thus, the CH_4 is not emitted only from the soil surface but also from tree stems and termites, which causes a vertical variation in CH_4 flux.

Measurement of CH_4 emissions to the atmosphere has largely relied on the static chamber technique and the eddy covariance technique (McDermitt et al., 2011). The chamber technique provides advantages, such as portability, low-cost and detectability of small-scale CH_4 ebullition events in a small sampling area (Nadeau et al., 2013). However, the method is very labour intensive, and is subject to uncertainties due to soil disturbance and insufficient gas mixing (Christiansen et al., 2011). In addition, the chamber technique usually excludes trees. Alternatively, the tower-based micrometeorological approaches, such as the eddy covariance technique, has now been widely used to measure ecosystem-scale CH_4 flux over a larger area (~103–105 m^2) (e.g. Nadeau et al., 2013; Song et al., 2015). The eddy covariance technique enables continuous flux measurement with minimal disturbance and allows us to quantify CH_4 flux on multiple time scales (Rinne et al., 2007).

In middle- and high-latitude peat ecosystems, many studies on CH_4 flux have been conducted by the eddy covariance technique (e.g. Rinne et al., 2007; Jackowicz-Korczyński et al., 2010; Nadeau et al., 2013; Olson et al., 2013; Song et al., 2015). In tropical 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_{CH4}) in each ecosystem, and examine its diurnal and seasonal variations;

ii) determine the responses of F_{CH4} 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

i) Wong GX, Hirata R, Hirano T, Kiew F, Aeries EB, Musin KK, Joseph WW, Lo KS, Melling L 2018: Micrometeorological measurement of methane flux above a tropical peat swamp forest. Agric. For. Meteorol., 256–257, 353–361.

ii) Wong GX, Hirata R, Hirano T, Kiew F, Aeries EB, Musin KK, Joseph WW, Lo KS, Melling L 2018: Methane balance of tropical peat ecosystems in Sarawak, Malaysia. Glob. Chang. Biol. (In progress)

iii) Wong GX, Hirata R, Hirano T, Kiew F, Aeries EB, Musin KK, Joseph WW, Lo KS, Melling L 2018: Comparison of methane flux measured by eddy covariance technique among three different tropical peat ecosystems. In International Symposium of Agricultural Meteorology 2018 (ISAM 2018). March 13–17, Fukuoka, Japan.

iv) Wong GX, Hirata R, Hirano T, Kiew F, Aeries EB, Musin KK, Joseph WW, Lo KS, Melling L 2017: Micrometeorological Measurement of Methane Flux above Tropical Peat Swamp Forests. ln Joint conference of AsiaFlux Workshop 2017 and the 15th Anniversary Celebration of ChinaFLUX. August 17–19, Beijing, China.

v) Wong GX, Hirata R, Hirano T, Kiew F, Aeries EB, Musin KK, Joseph WW, Lo KS, Melling L 2017: Micrometeorological Measurement of Methane Flux above a Tropical Peat Swamp Forest. In International Symposium of Agricultural Meteorology 2017 (ISAM 2017). March 27–30, Aomori, Japan. (Best poster)

vi) Wong GX, Hirata R, Hirano T, Kiew F, Aeries EB, Musin KK, Joseph WW, Lo KS, Melling L 2016: Eddy Covariance Measurement of Methane Flux above a Primary Tropical Peat Swamp Forest in Sarawak, Malaysia. In Proceedings of 15th International Peat Congress (IPC). August 15–19, Sarawak, Malaysia.

Chapter 2

Material and methods

2.1 Site description

This study was conducted in three different ecosystems on coastal peat (Dommain 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 (T_a) (± 1 SD) in the same period was 26.5 ± 0.2°C at the nearest meteorology station in Kuching International Airport.

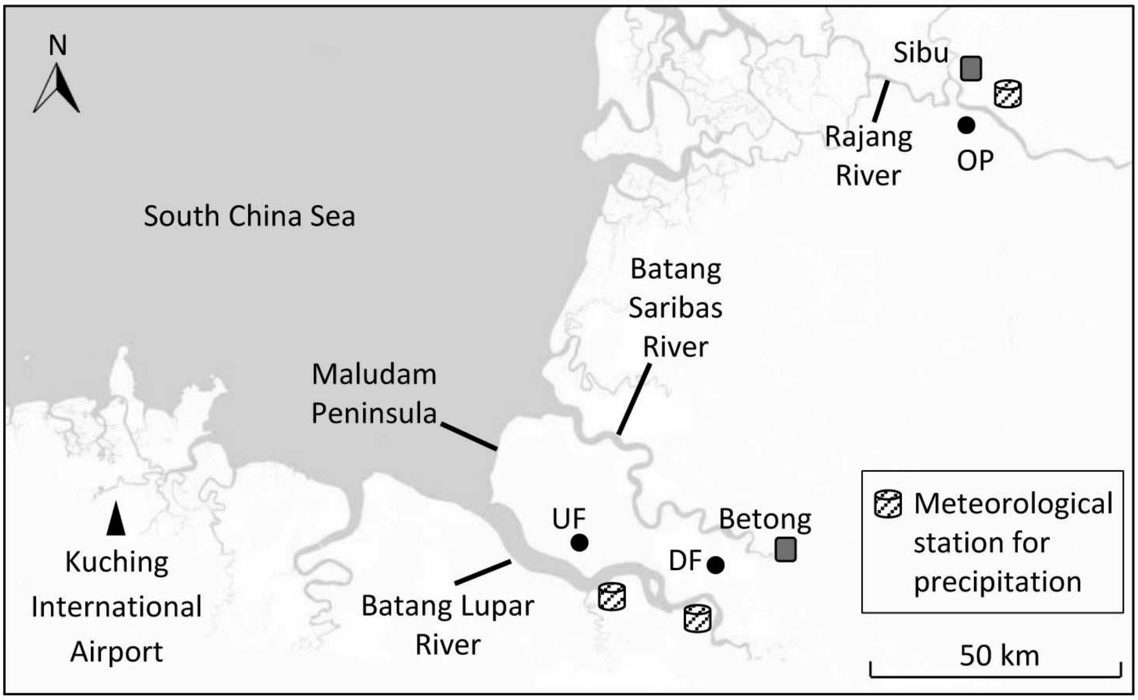


Figure 2.1 Map of the sites.

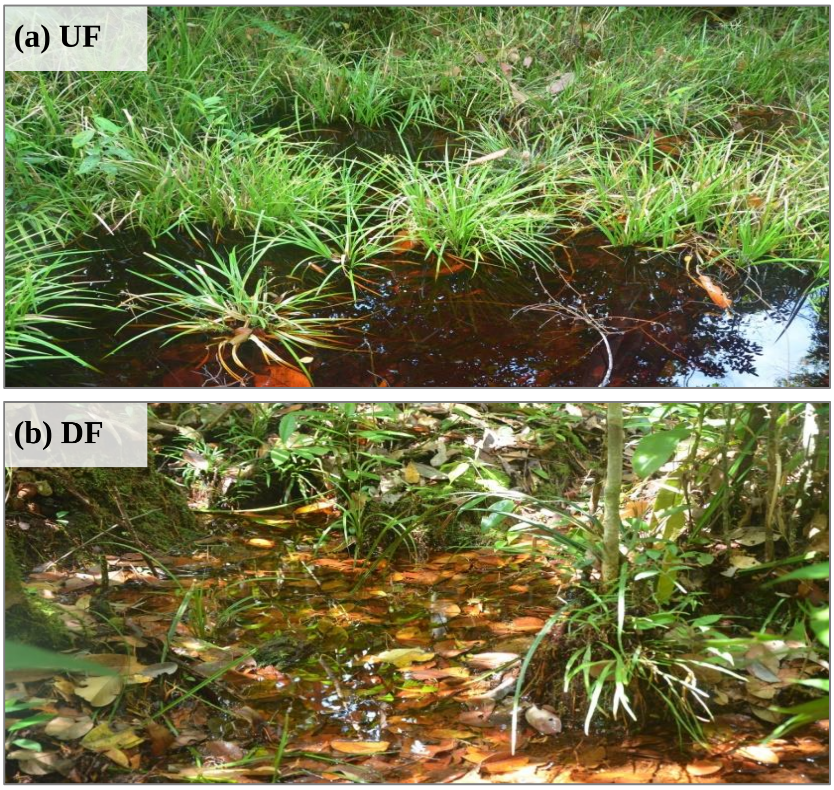


Figure 2.2 GWL rises aboveground during the wettest period at (a) UF and (b) DF.

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 pandanus (Figure a).

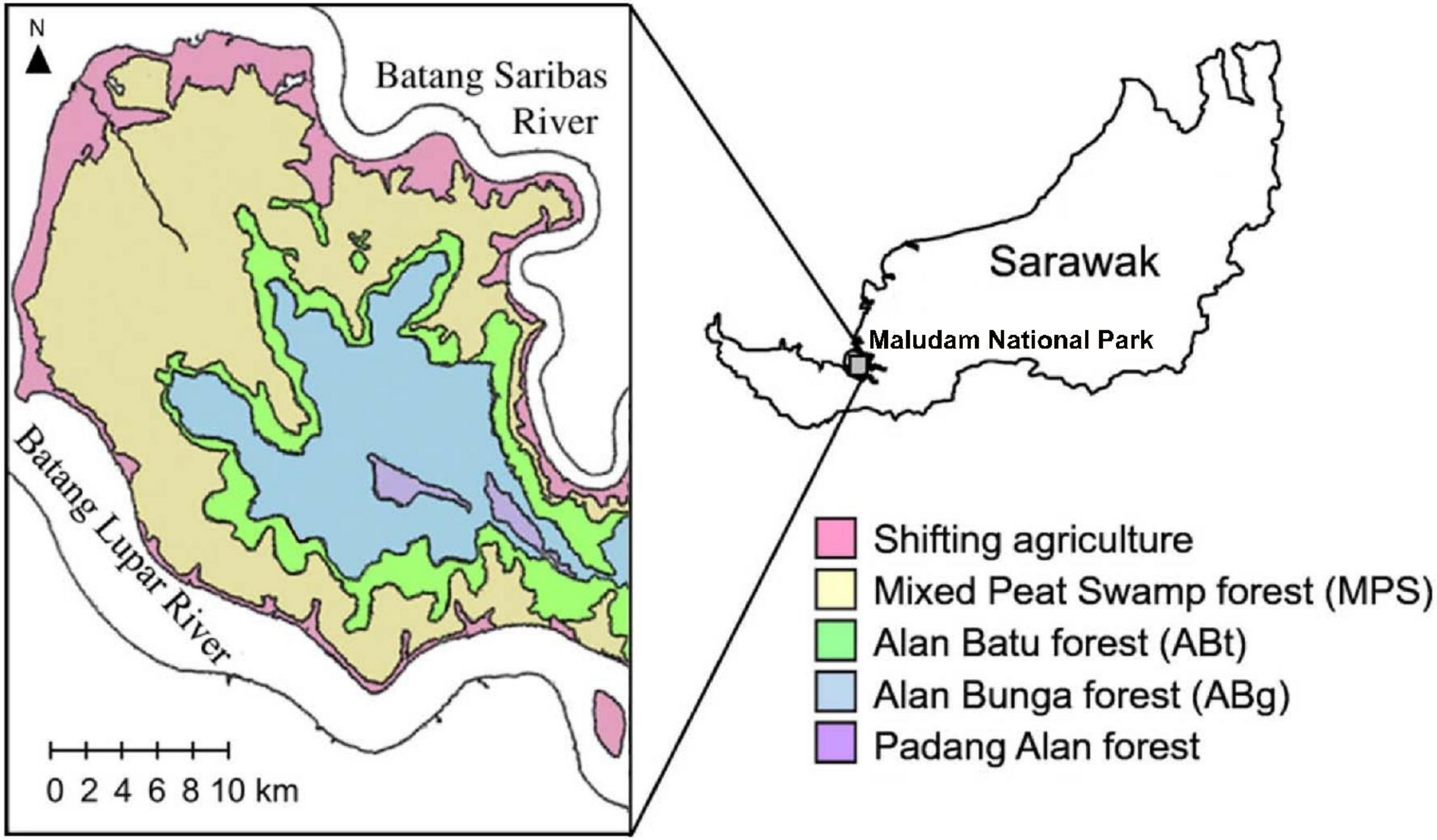


Figure 2.3 The zonal communities in Maludam National Park (Melling, 2016; Sangok et al., 2017).

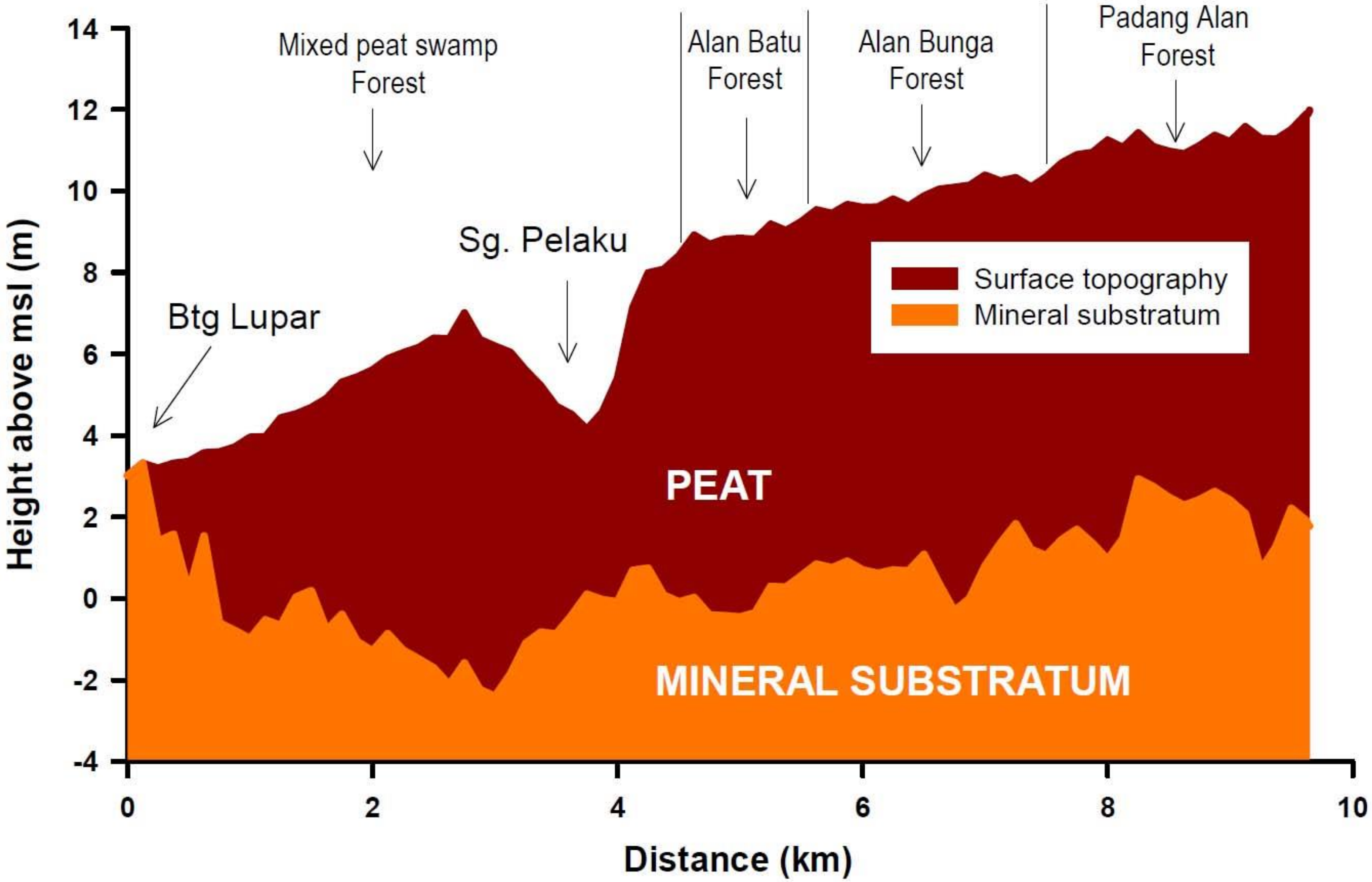


Figure 2.4 The zonal communities across the peat dome at Maludam National Park (Melling, 2016), and UF is in the Alan Batu forest.

Table 2.1 Description of Mixed Peat Swamp, Alan Batu, Alan Bunga and Padang Alan forests (Anderson, 1961; Melling, 2016).

Zonal community	Characteristic
Mixed Peat Swamp forest	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.
Alan Batu forest	Dominated by scattered very large trees (> 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.
Alan Bunga forest	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.
Padang Alan forest	Dense and even canopy forest where it composed of relatively small-sized trees (< 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.

Table 2.2 Site information of the protected forest (UF), selectively-logged secondary forest (DF) and oil palm plantation (OP).

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

*0 to 5-cm-thick surface soil.

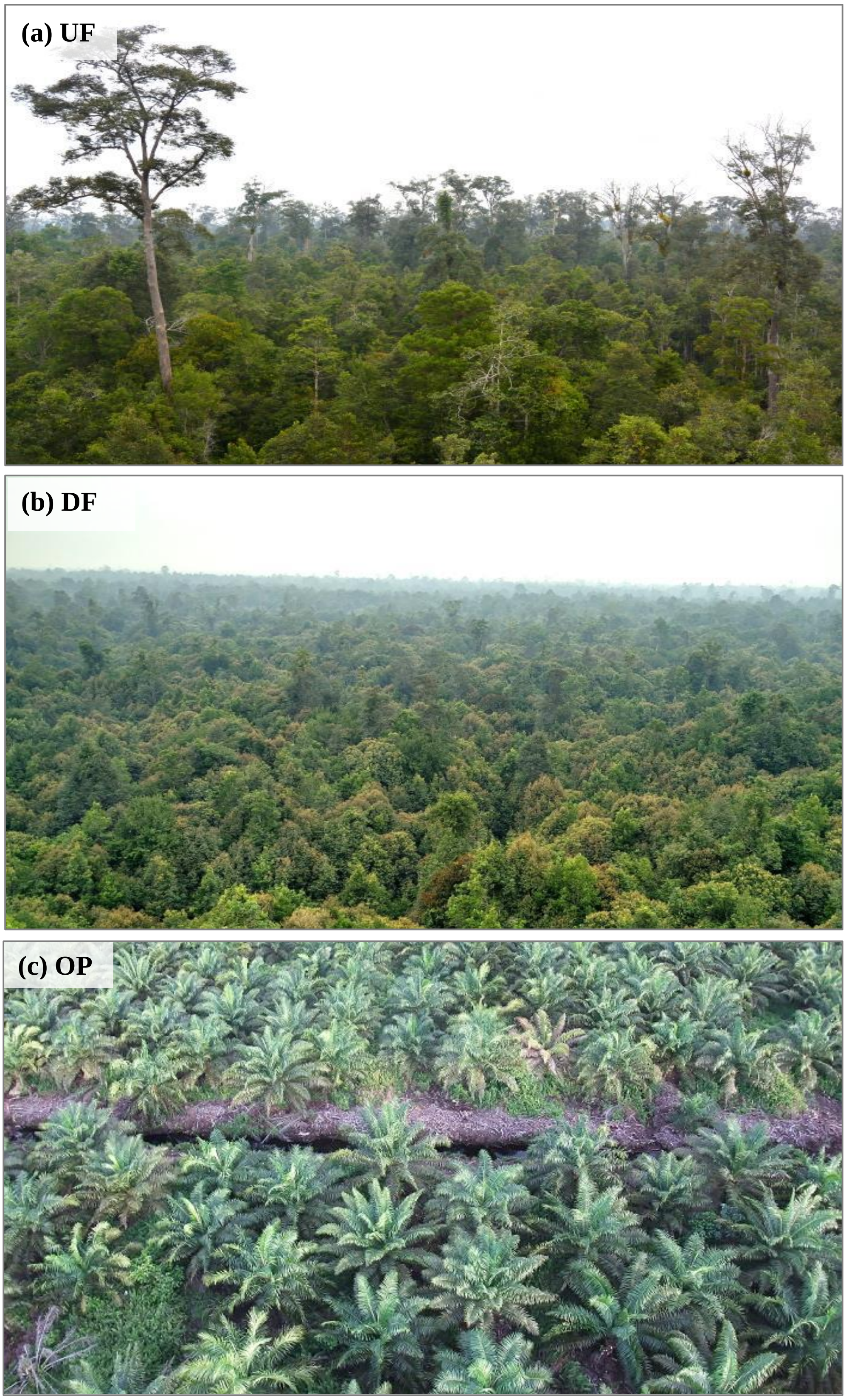


Figure 2.5 The canopies of (a) UF, (b) DF and (c) OP.

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 in1980s, 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 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.

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.

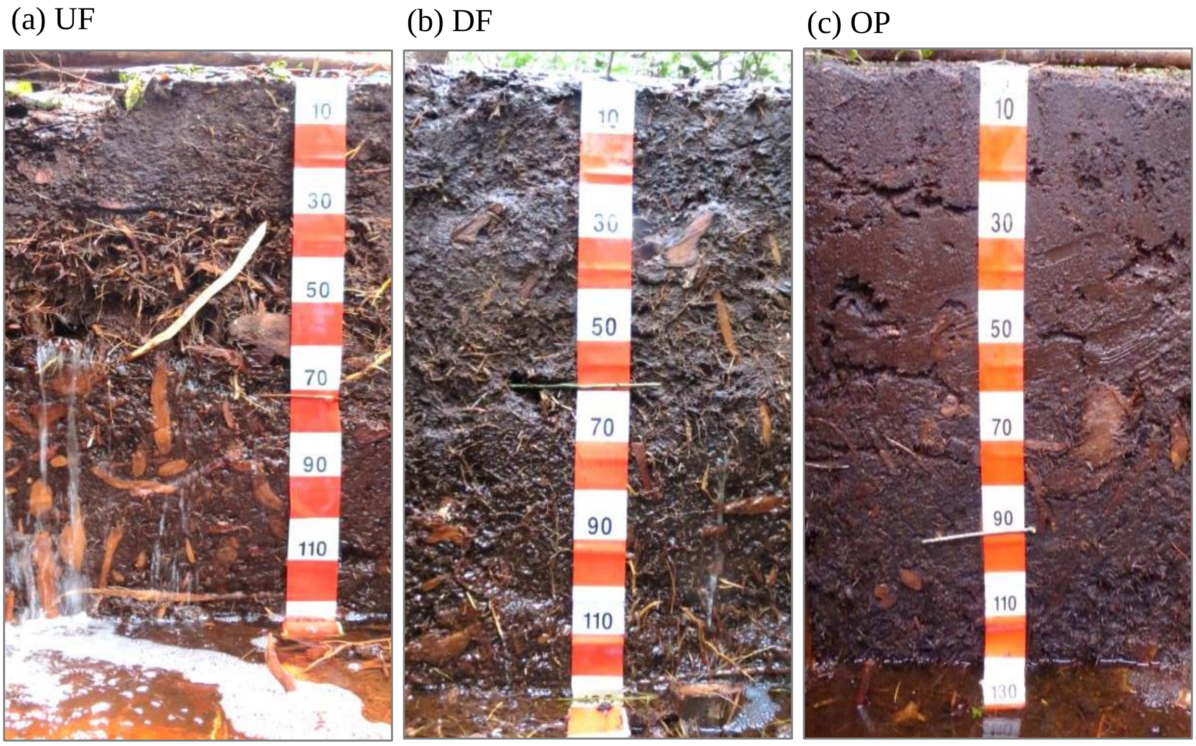

(a) UF
(b) DF
(c) OP

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

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 CO_2, 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 CO_2/H_2O analyser (LI-7500A, Li-Cor Inc., Lincoln, NE, USA), and an open-path CH_4 analyser (LI-7700, Li-Cor Inc.). 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.). T_a 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 (T_s) 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).

(a) UF

(b) DF

(c) OP

Figure 2.10 Flux towers of (a) UF, (b) DF and (c) OP. All tower heights are 41 m.

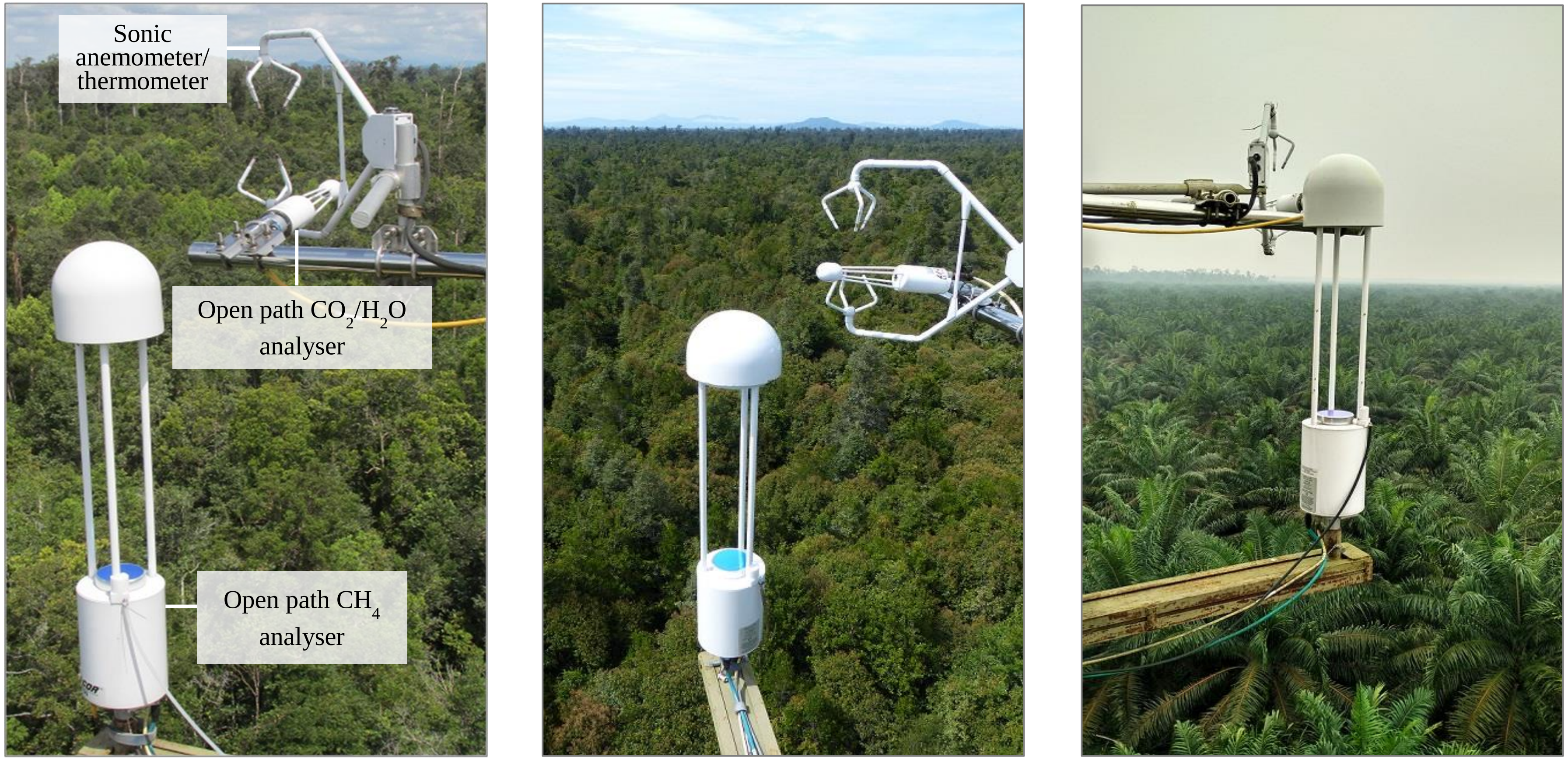

(a) UF (b) DF (c) OP

Figure 2.11 Eddy flux sensors of (a) UF, (b) DF and (c) OP.

(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) sensor

(h) Piezometer

Figure 2.12 Meteorological sensors of (a) quantum sensor, (b) radiometer, (c) temperature and relative humidity probes, (d) 3-cup anemometer and wine 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.

Sensor	Site		
	UF (m)	DF (m)	OP (m)
Quantum sensor	40	40	40
Radiometer	40	40	40
Temperature and relative humidity probes	40	40	20
3-cup anemometer and wind vane	40	40	20

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_{CH4} (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.

$$F_{CH4} = F_C + F_S$$

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 (≥ 8 m). In fact, the F_S should be calculated using CH_4 profile data to accurately determine F_{CH4}. 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_{CH4} 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_{CH4} 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_{CH4} 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_{CH4} was determined to be 0.14 ms^{-1} for UF, whereas no threshold was found for DF and OP.

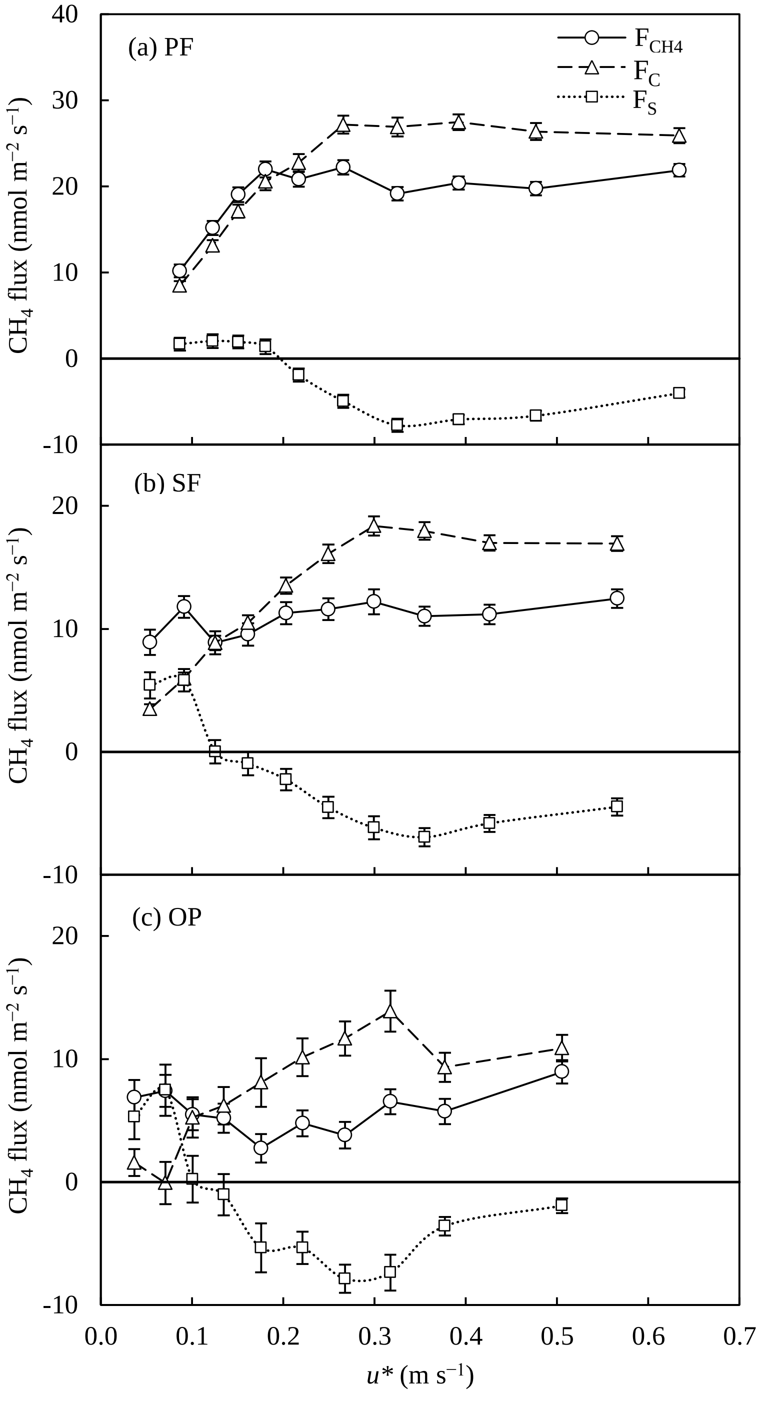


Figure 2.13 Relationship of CH$_4$ fluxes [net ecosystem CH$_4$ exchange (F_{CH4}), eddy CH$_4$ flux (F_C) and CH$_4$ storage change (F_S) with friction velocity (*u**) for entire days at (a) UF, (b) DF and (c) OP. Flux data were sorted by *u** and binned into decile groups. Vertical bars denote standard errors.

2.6 Gap filling

After the quality control, the surviving rates of F_{CH4} 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_{CH4}. 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_{CH4} 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_{CH4} 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 (± 1 SD) was 2560 ± 249 mm yr^{-1}, which was 20% less than the mean annual long-term precipitation (2005-2014; ± 1 SD) of 3201 ± 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).

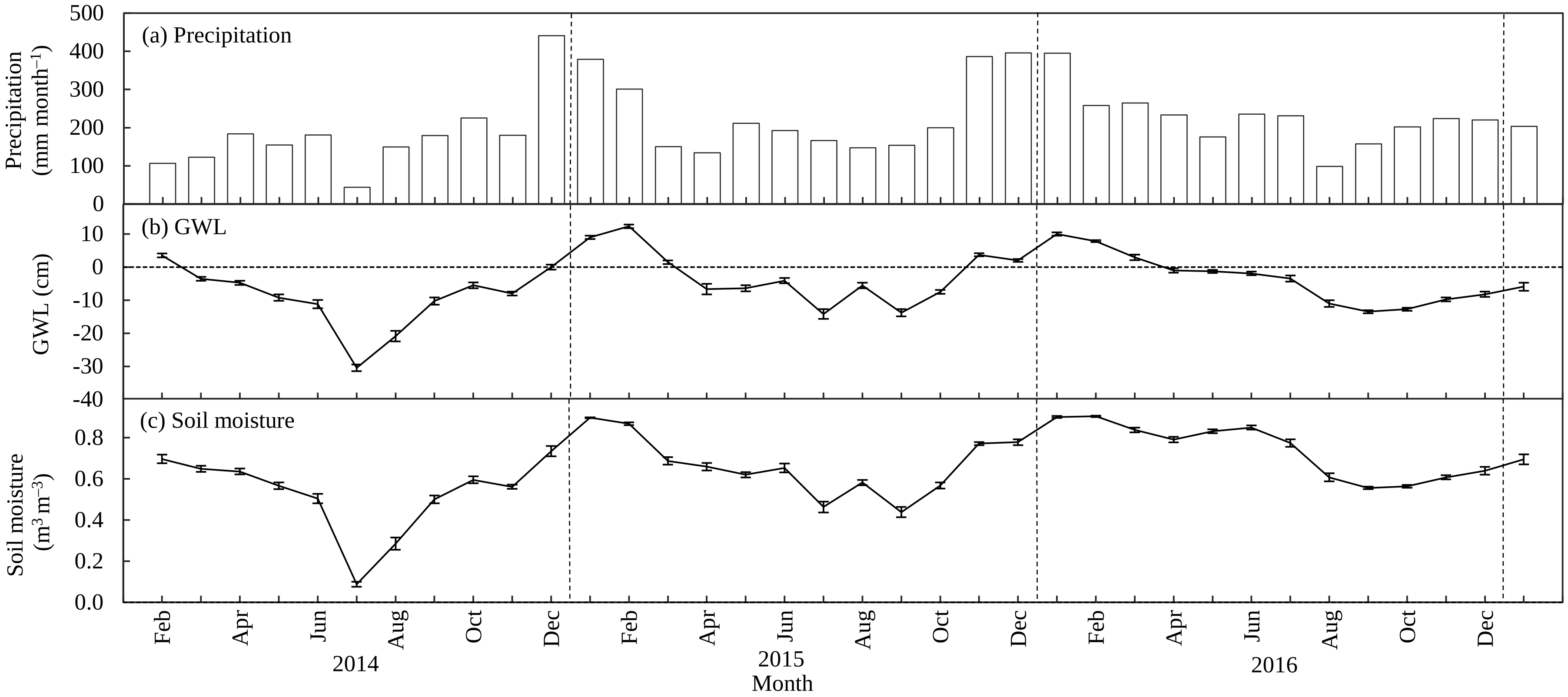


Figure 3.1 Variations in monthly (a) precipitation, (b) groundwater level (GWL) and (c) soil moisture from February 2014 to January 2017. Vertical bars denote standard errors.

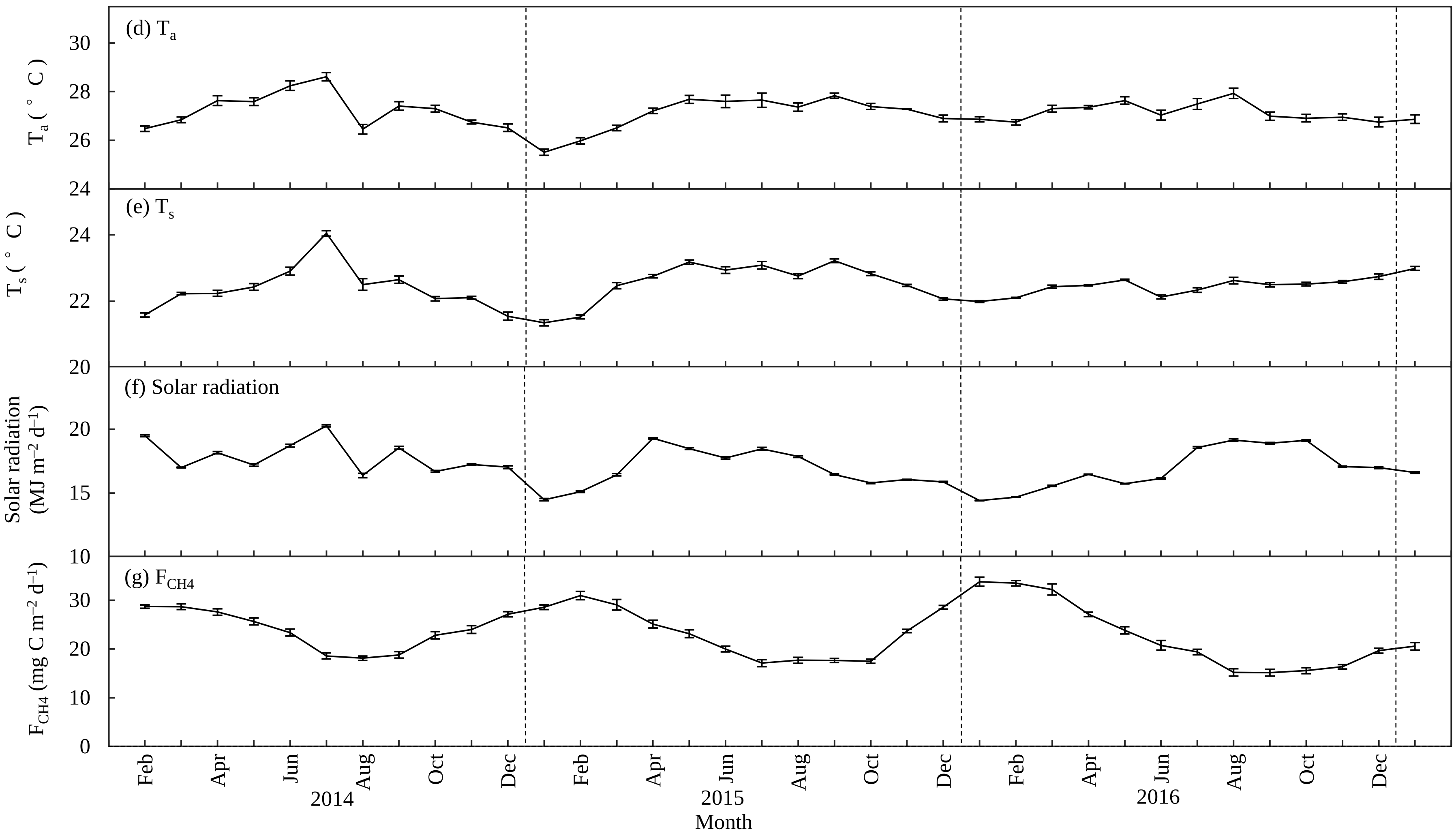


Figure 3.1 (continued) Variations in monthly (d) air temperature (T_a), (e) soil temperature (T_s), (f) solar radiation and (g) gap-filled daily net ecosystem CH_4 exchange (F_{CH4}) from February 2014 to January 2017. Vertical bars denote standard errors.

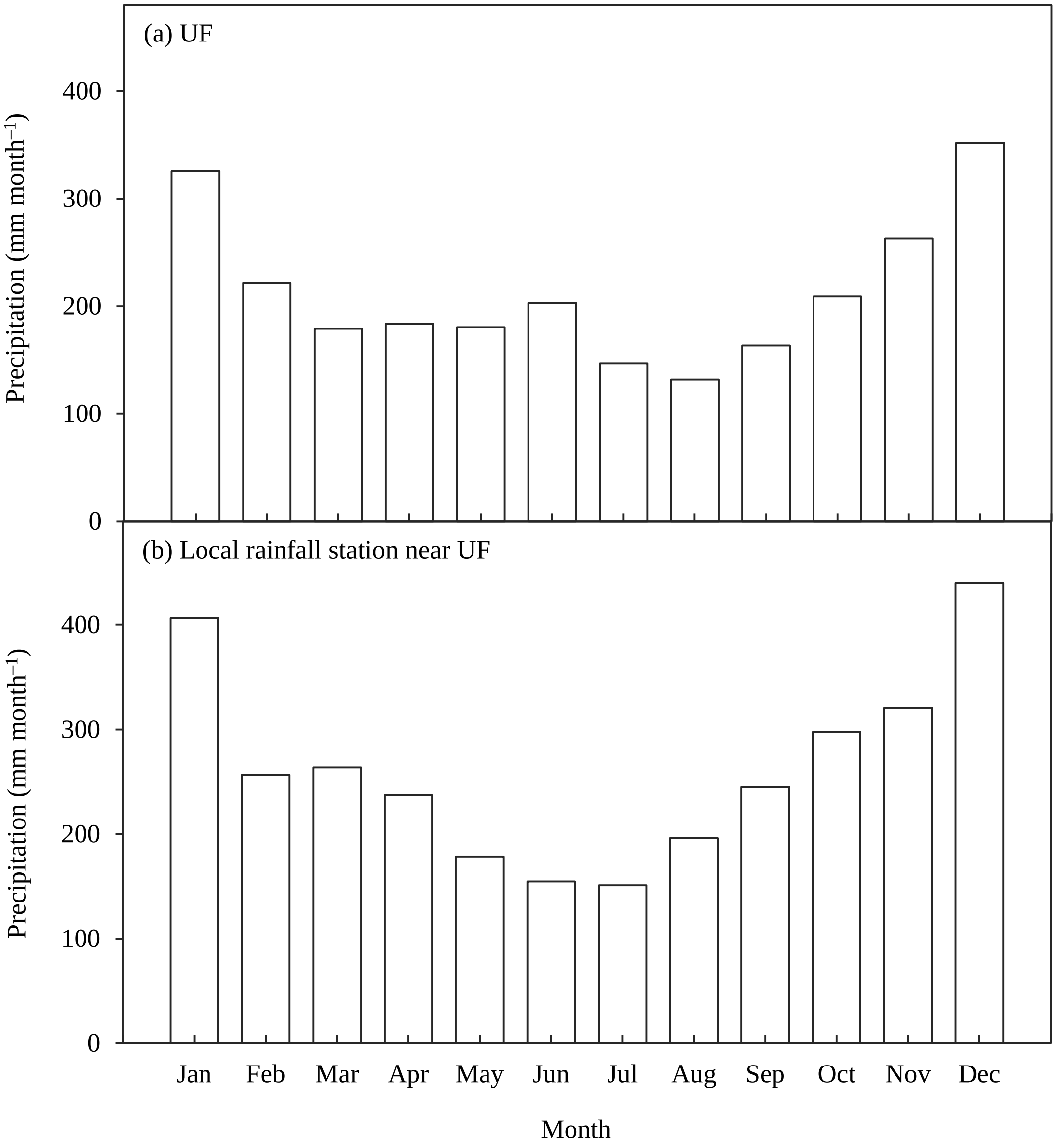


Figure 3.2 Ensemble mean seasonal variations in precipitation at (a) UF (3 years) and (b) local rainfall station near UF (10 years).

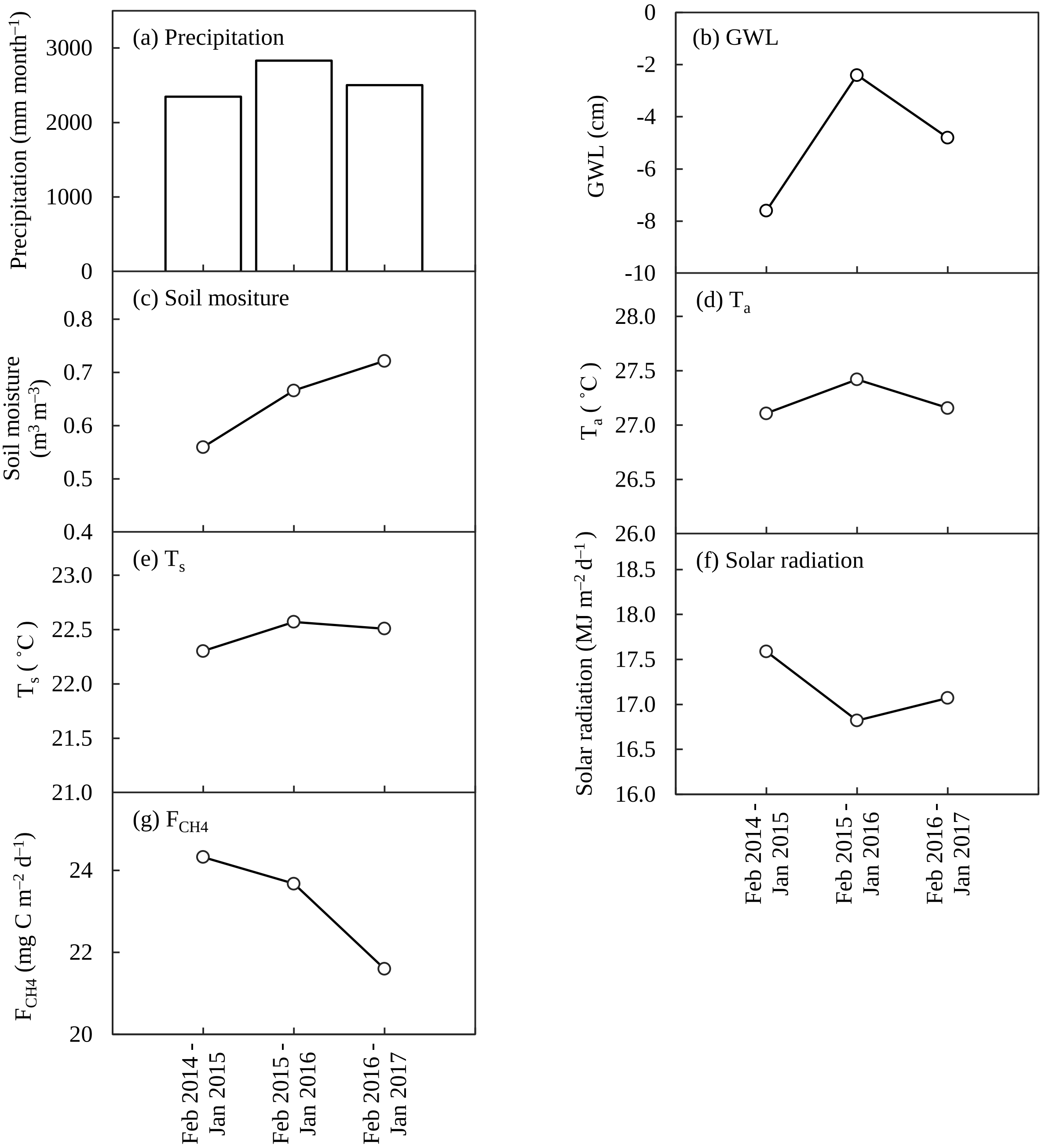


Figure 3.3 Variations in annual (a) precipitation (b) groundwater level (GWL), (c) soil moisture, (d) air temperature (T_a), (e) soil temperature (T_s), (f) solar radiation and (g) gap-filled daily net ecosystem CH_4 exchange (F_{CH4}) from February (Feb) 2014 to January (Jan) 2017.

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

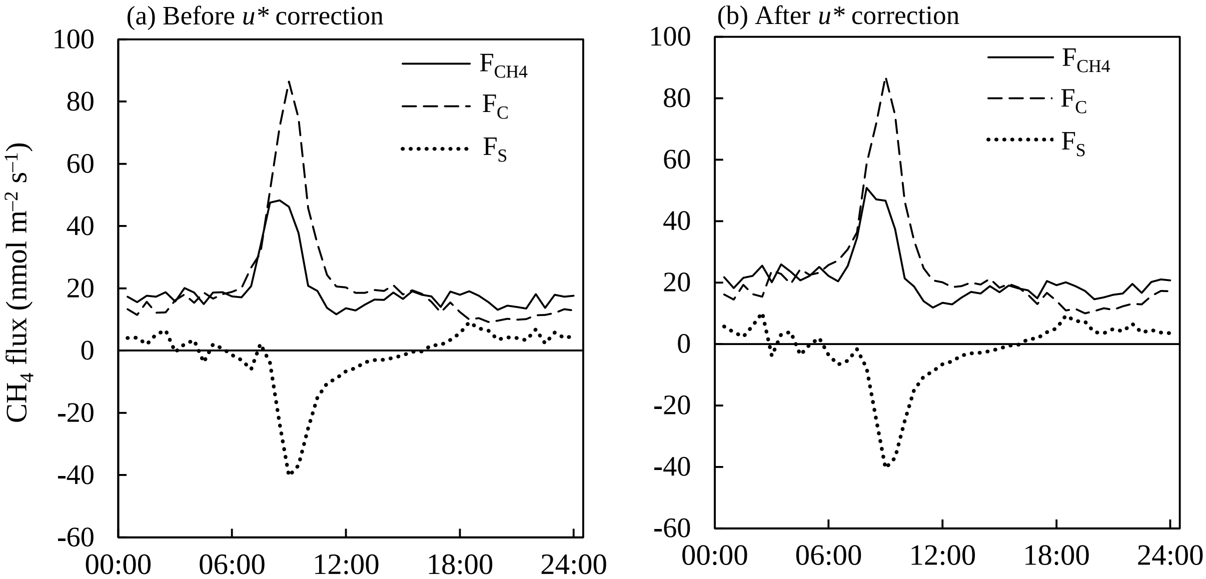


Figure 3.4 Ensemble mean diurnal variations in net ecosystem CH_4 exchange (F_{CH4}), eddy CH_4 flux (F_C) and CH_4 storage change (F_S) from February 2014 to January 2017 (a) before friction velocity ($u*$) correction and (b) after $u*$ correction.

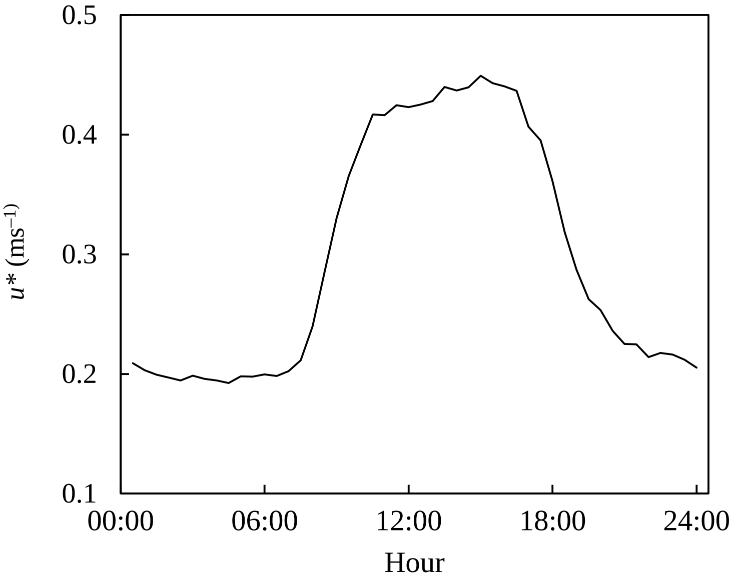


Figure 3.5 Ensemble mean diurnal variations friction velocity (*u**) from February 2014 to January 2017. Increased in turbulent mixing was started at 07:00.

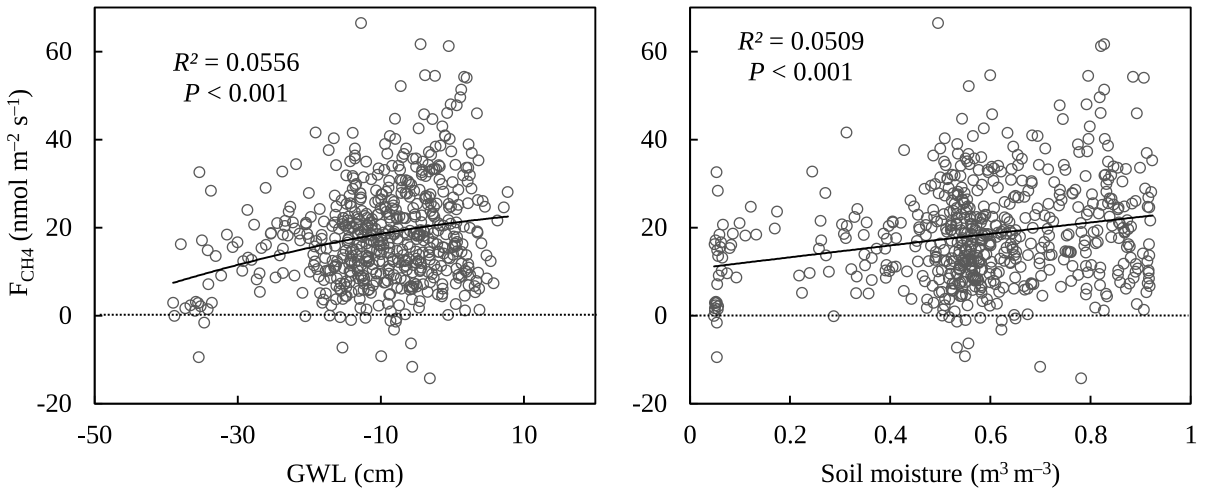
3.3 Seasonal and inter-annual variations in F_{CH4}

Mean half-hourly measured F_{CH4} (± 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 CH_4 source to the atmosphere. On a monthly basis, gap-filled F_{CH4} was always positive (Fig. 3.1g). Seasonal variation in gap-filled F_{CH4} was similar with GWL and soil moisture (Figs. 3.1b and 3.1c) The F_{CH4} 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_{CH4} showed a V-shaped variation and generally consistent in all annual periods. Peak F_{CH4} occurred in January or February when the GWL was high or above soil surface. Annual F_{CH4} in the form of mean monthly values showed a decreasing trend during 3 years period (Fig. 3.3g).

3.4 Responses of F_{CH4} to environmental variables

Influence of environmental variables on F_{CH4} 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_{CH4} were determined, only if the number of measured data was more than nine on each day. The relationships of the F_{CH4} 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_{CH4} 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_{CH4} 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_{CH4}.

(a) F_{CH4} vs GWL (b) F_{CH4} vs soil moisture



(c) F_{CH4} vs T_a (d) F_{CH4} vs T_s

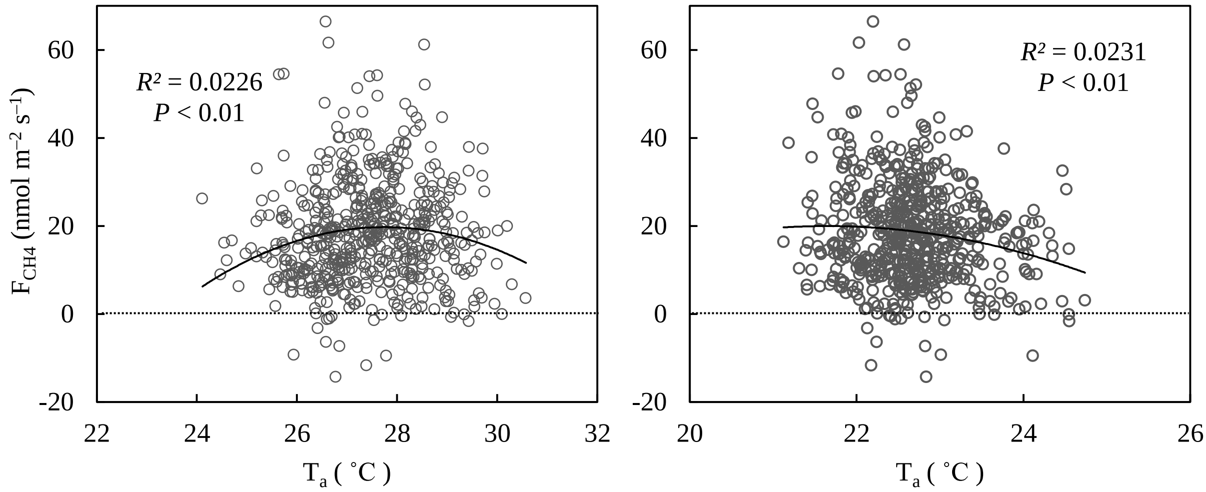


Figure 3.6 Responses of net ecosystem CH_4 exchange (F_{CH4}) to (a) groundwater level (GWL), (b) soil moisture, (c) air temperature (T_a) and (d) soil temperature (T_s) on a daily basis. The relationships were determined using measured data and regression curves were drawn.

Table 3.1 Relationships of F_{CH4} with groundwater level (GWL), soil moisture, air temperature (T_a) and soil temperature (T_s) on linear and curvilinear bases.

Environmental variable	F_{CH4} (nmol m^{-2} s^{-1})	
	Linear	Curvilinear
GWL (cm)	$y = 0.31x + 21.4$ ($R^2 = 0.0545$)*	$y = -0.0035x^2 + 0.21x + 21.0$ ($R^2 = 0.0556$)*
Soil moisture (m^3 m^{-3})	$y = 13.2x + 10.7$ ($R^2 = 0.0509$)*	$y = -0.63x^2 + 13.8x + 10.5$ ($R^2 = 0.0509$)*
T_a (˚C)	–	$y = -1.02x^2 + 56.4x - 763.4$ ($R^2 = 0.0226$)†
T_s (˚C)	$y = -2.63x + 78.0$ ($R^2 = 0.0200$)*	$y = -1.11x^2 + 47.9x - 498.49$ ($R^2 = 0.0231$)†

† < 0.01, * < 0.001

3.5 Annual CH_4 balance

Annual F_{CH4} (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_{CH4} among the annual period was within 1 g C m^{-2} yr^{-1}. Mean annual F_{CH4} (± 1 SD) was 8.46 ± 0.51 g C m^{-2} yr^{-1}. To examine the effect of the correction, mean annual F_{CH4} 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).

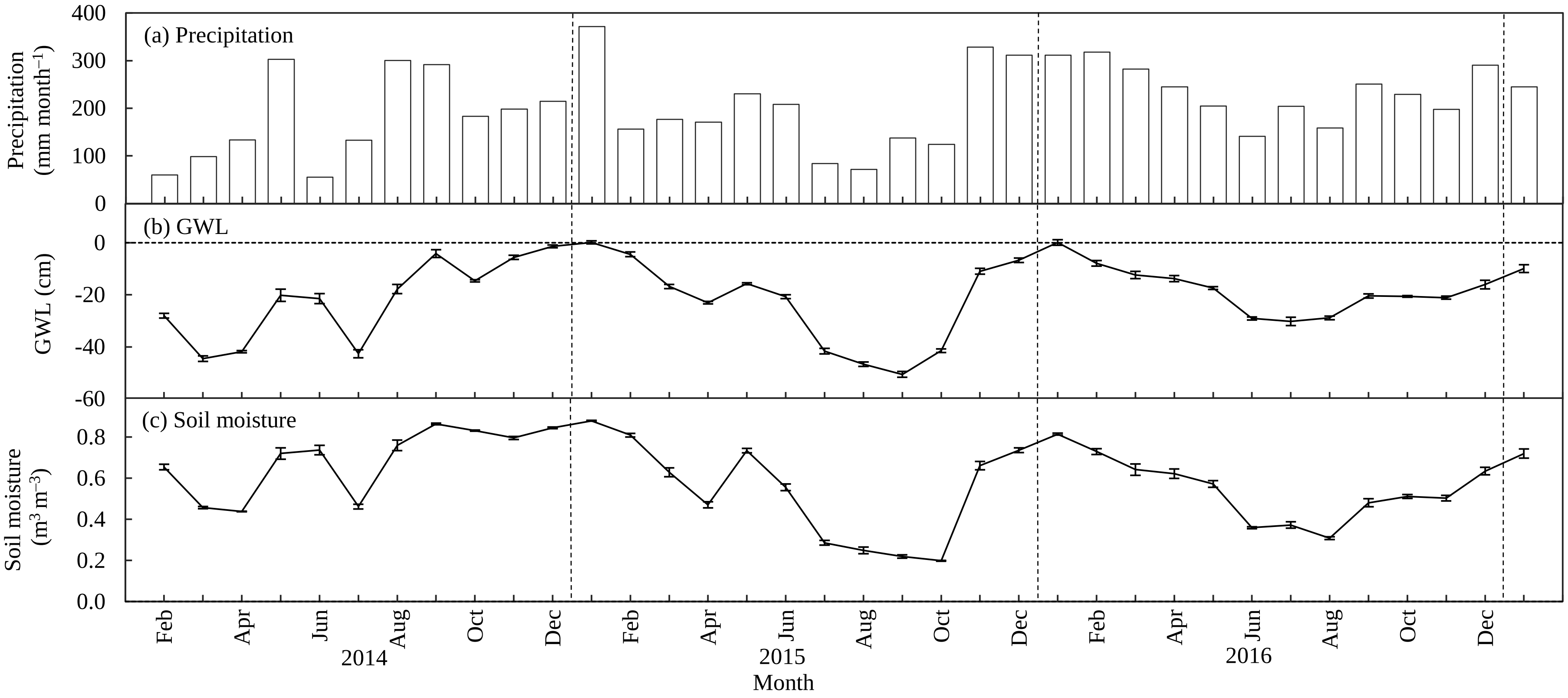


Figure 4.1 Variations in monthly (a) precipitation, (b) groundwater level (GWL) and (c) soil moisture and from February 2014 to January 2017. Vertical bars denote standard errors.

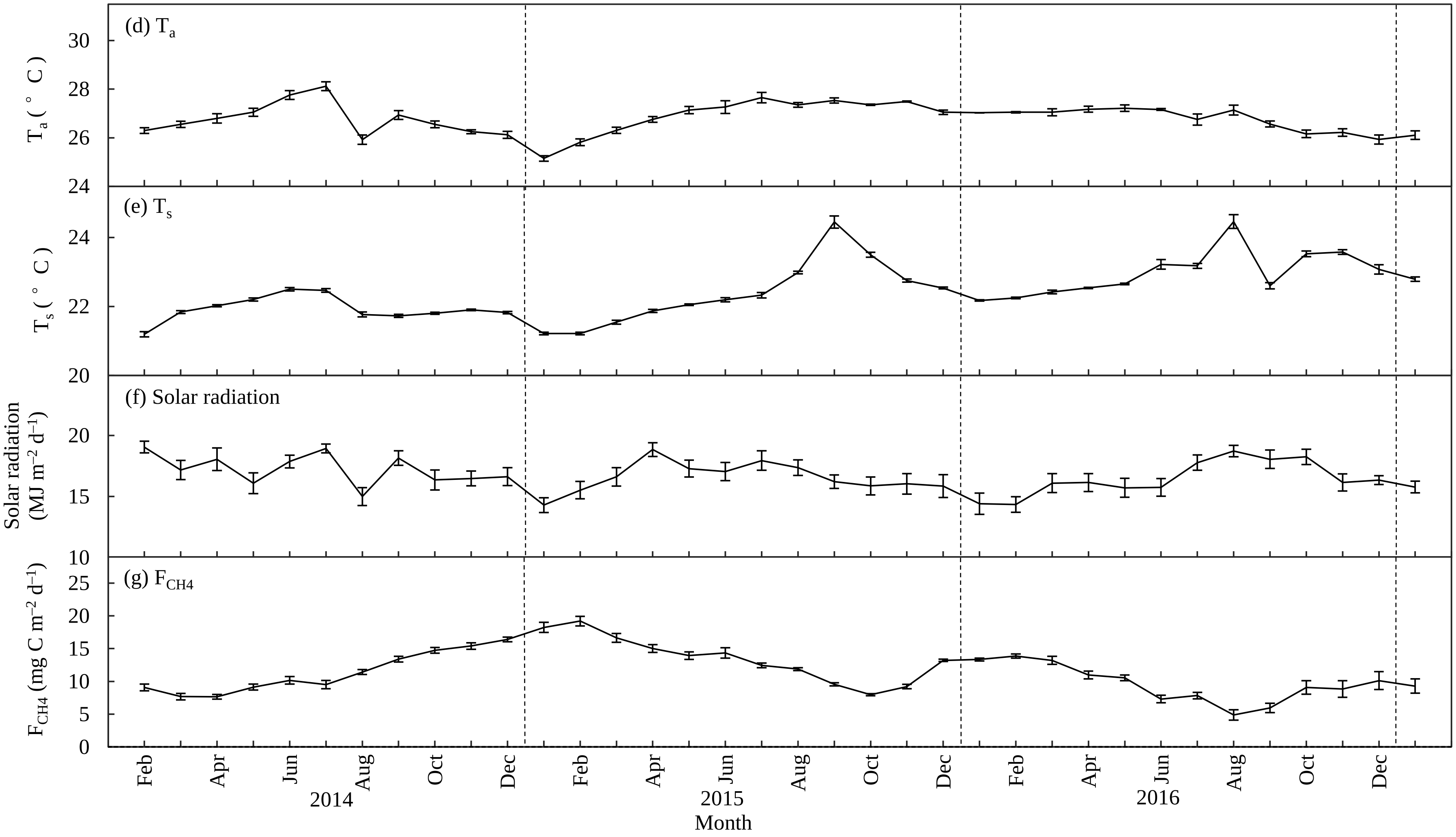


Figure 4.1 (continued) Variations in monthly (d) air temperature (T_a), (e) soil temperature (T_s), (f) solar radiation and (g) gap-filled daily net ecosystem CH_4 exchange (F_{CH4}) from February 2014 to January 2017. Vertical bars denote standard errors.

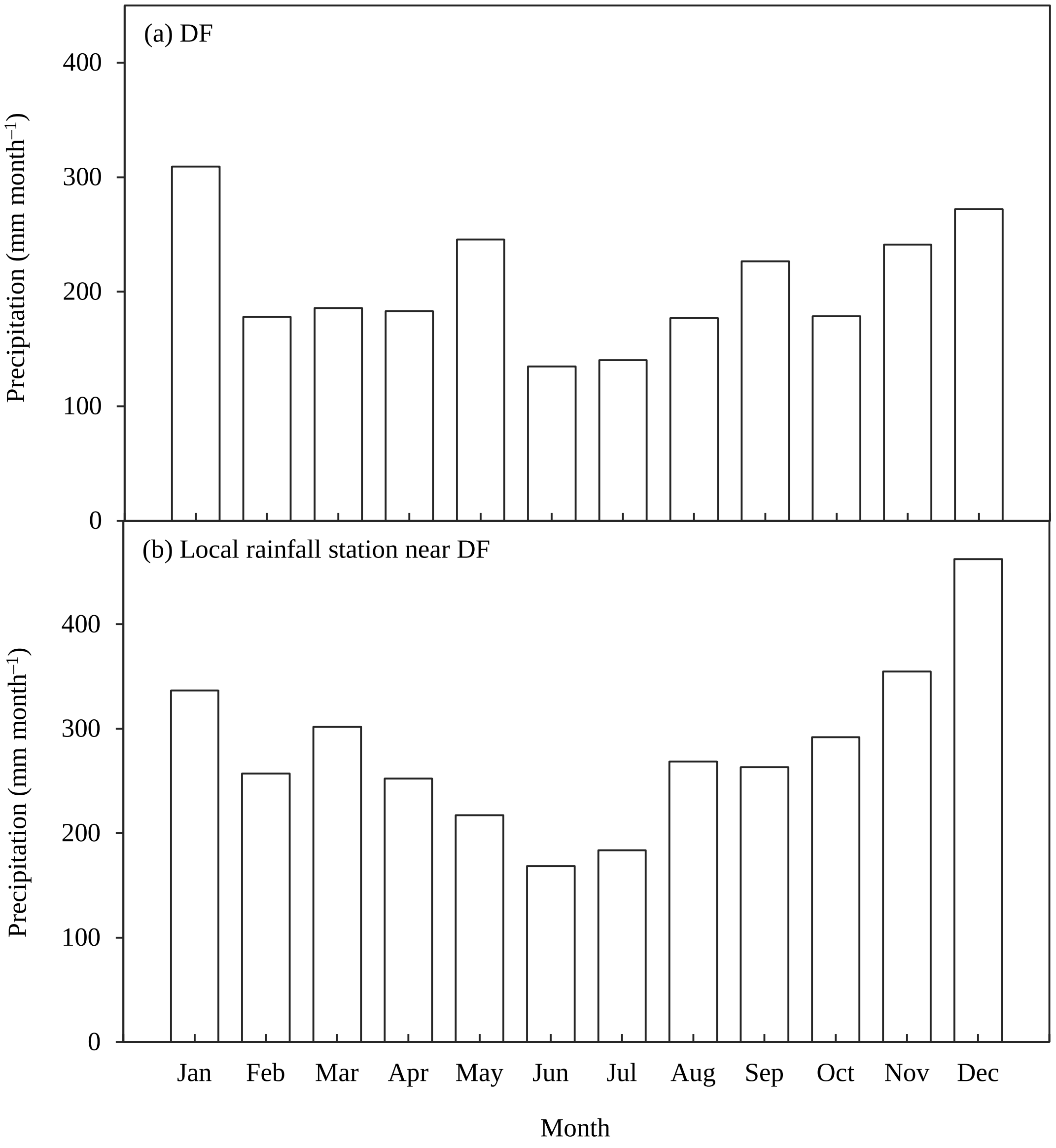


Figure 4.2 Ensemble mean seasonal variations in precipitation at (a) DF (3 years) and (b) local rainfall station near DF (10 years).

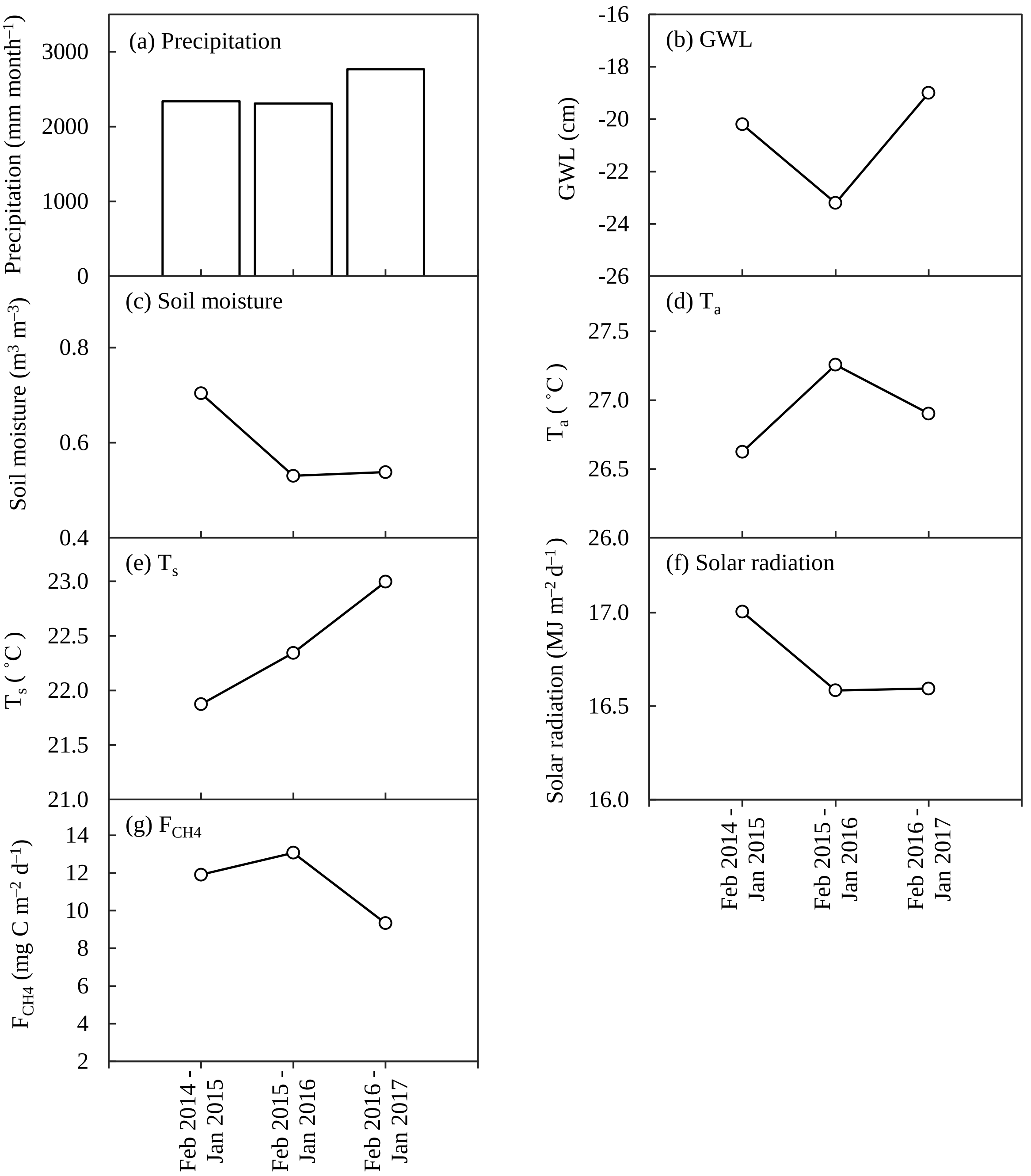


Figure 4.3 Variations in annual (a) precipitation (b) groundwater level (GWL), (c) soil moisture, (d) air temperature (T_a), (e) soil temperature (T_s), (f) solar radiation and (g) gap-filled daily net ecosystem CH_4 exchange (F_{CH4}) from February (Feb) 2014 to January (Jan) 2017.

4.2 Diurnal variations in CH_4 fluxes

Similar with UF, both F_{CH4} 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_{CH4}. There was no clear diurnal pattern in F_{CH4}, and the F_{CH4} was ranges from 6.5 to 15.9 nmol m^{-2} s^{-1}.

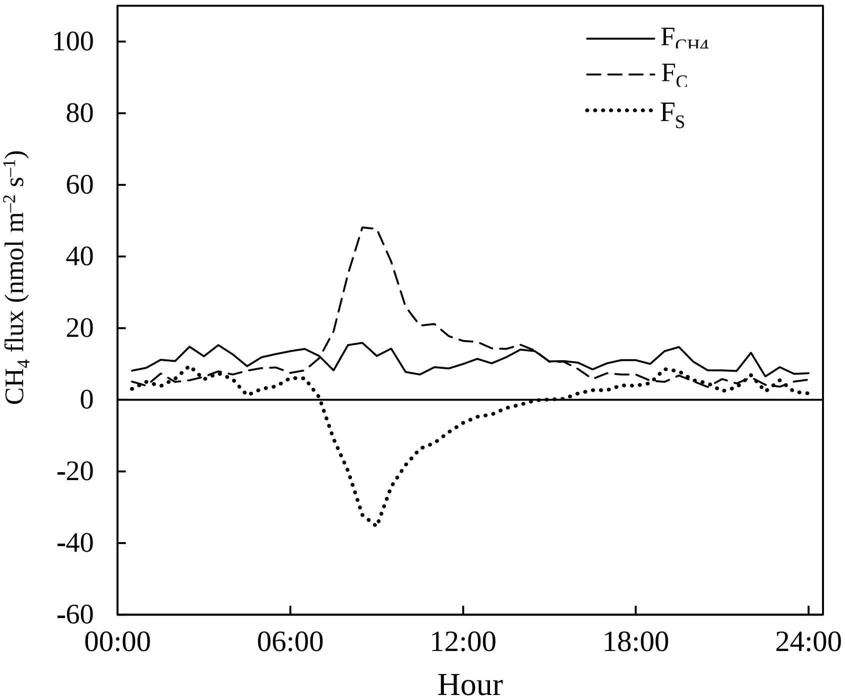


Figure 4.4 Ensemble mean diurnal variations in net ecosystem CH_4 exchange (F_{CH4}), eddy CH_4 flux (F_C) and CH_4 storage change (F_S) from February 2014 to January 2017.

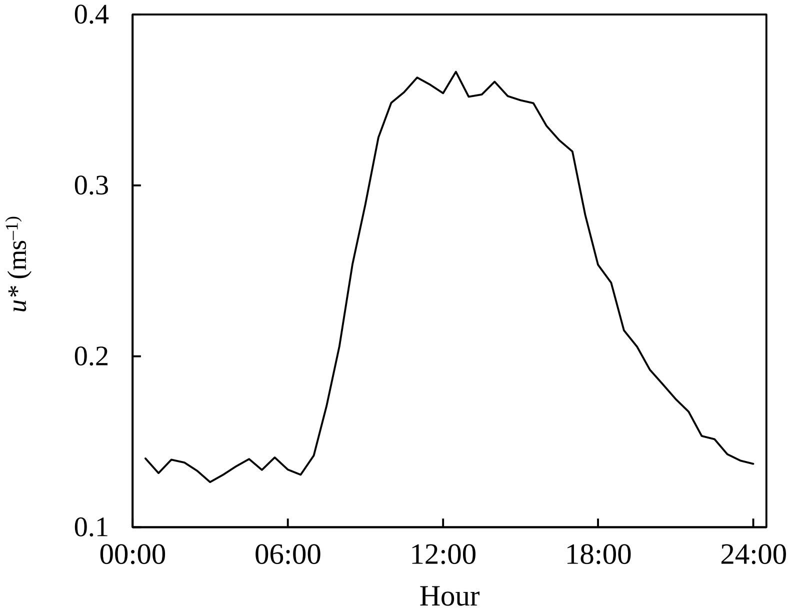


Figure 4.5 Ensemble mean diurnal variations friction velocity (*u**) from February 2014 to January 2017. Increased in turbulent mixing was started at 07:00.

4.3 Seasonal and inter-annual variations in F_{CH4}

Mean of measured half-hourly F_{CH4} (± 1 SD) was 10.9 ± 37.8 nmol m^{-2} s^{-1}, and thus the site was a net CH_4 source. On a monthly basis, gap-filled F_{CH4} was always positive (Fig. 4.1g). Seasonal variation in gap-filled F_{CH4} was almost similar with GWL and soil moisture (Figs. 4.1b and 4.1c). There was positive correlations between of F_{CH4} with GWL ($r = 0.58$; $P < 0.001$) and soil moisture ($r = 0.61$; $P < 0.001$). The peak F_{CH4} was 19.2 mg C m^{-2} d^{-1} in February 2015 when the GWL was above the soil surface. Annual F_{CH4} (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 FCH_4 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.

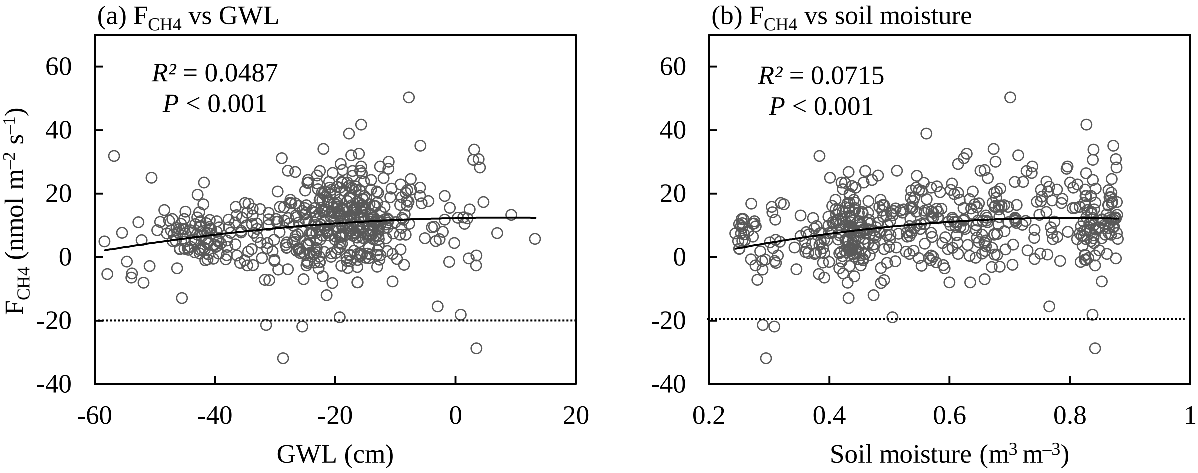


Figure 4.6 Responses of net ecosystem CH_4 exchange (F_{CH4}) to (a) groundwater level (GWL) and (b) soil moisture on a daily basis. The relationships were determined using measured data and regression curves were drawn.

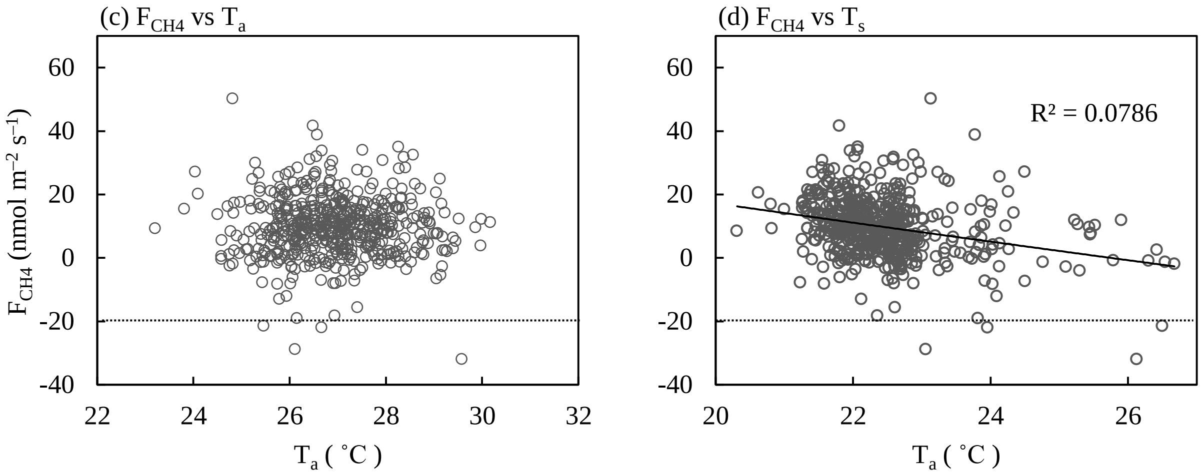


Figure 4.6 (continued) Responses of net ecosystem CH_4 exchange (F_{CH4}) to (c) air temperature (T_a) and (d) soil temperature (T_s) on a daily basis. The relationships were determined using measured data and regression curves were drawn.

Table 4.1 Relationships of F_{CH4} with groundwater level (GWL), soil moisture, air temperature (T_a) and soil temperature (T_s) on linear and curvilinear bases ($P < 0.001$).

Environmental variable	F_{CH4} (nmol m^{-2} s^{-1})	
	Linear	Curvilinear
GWL (cm)	$y = 0.16x + 13.4$ ($R^2 = 0.0457$)	$y = -0.0023x^2 + 0.037x + 12.3$ ($R^2 = 0.0487$)
Soil moisture (m^3 m^{-3})	$y = 13.1x + 2.2$ ($R^2 = 0.0613$)	$y = -31.8x^2 + 50.6x - 7.8$ ($R^2 = 0.0715$)
T_s (˚C)	$y = -3.0x + 76.7$ ($R^2 = 0.0786$)	$y = 0.015x^2 - 3.7x + 84.6$ ($R^2 = 0.0786$)

4.5 Annual CH_4 balance

Annual F_{CH4} (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_{CH4} of the annual periods was within 1.5 g C m^{-2} yr^{-1}. Mean annual F_{CH4} (± 1 SD) was 4.17 ± 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).

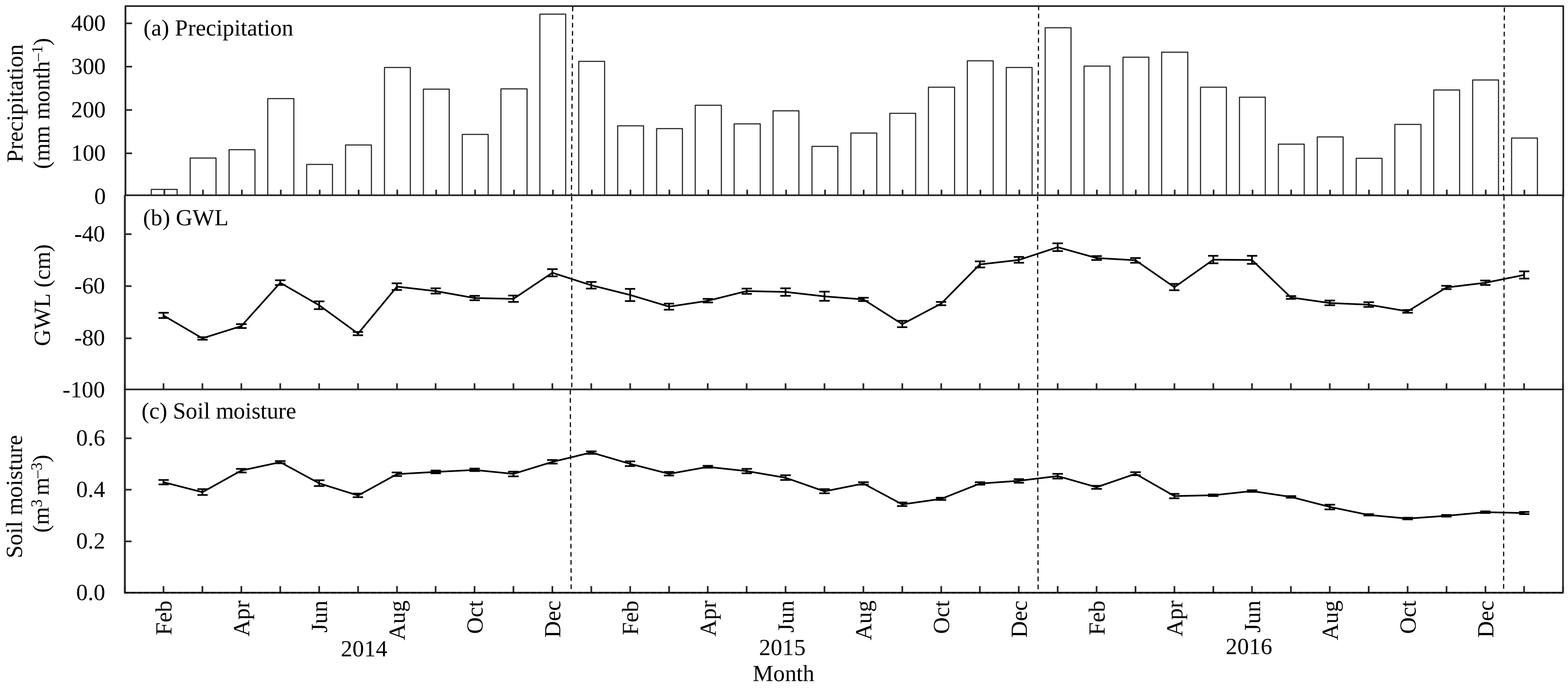


Figure 5.1 Variations in monthly (a) precipitation, (b) groundwater level (GWL) and (c) soil moisture from February 2014 to January 2017. Vertical bars denote standard errors.

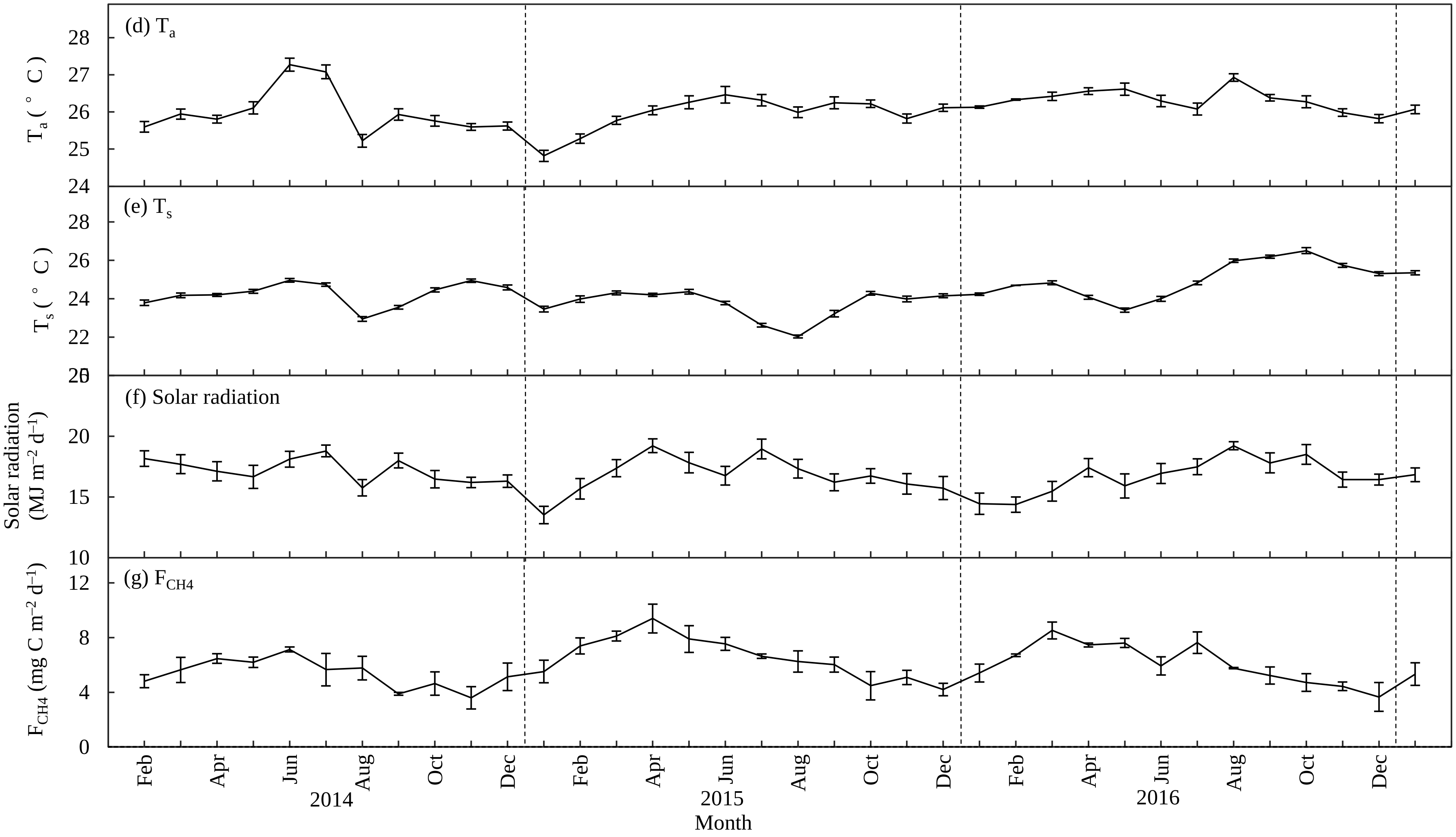


Figure 5.1 (continued) Variations in monthly (d) air temperature (T_a), (e) soil temperature (T_s), (f) solar radiation and (g) gap-filled daily net ecosystem CH_4 exchange (F_{CH4}) from February 2014 to January 2017. Vertical bars denote standard errors.

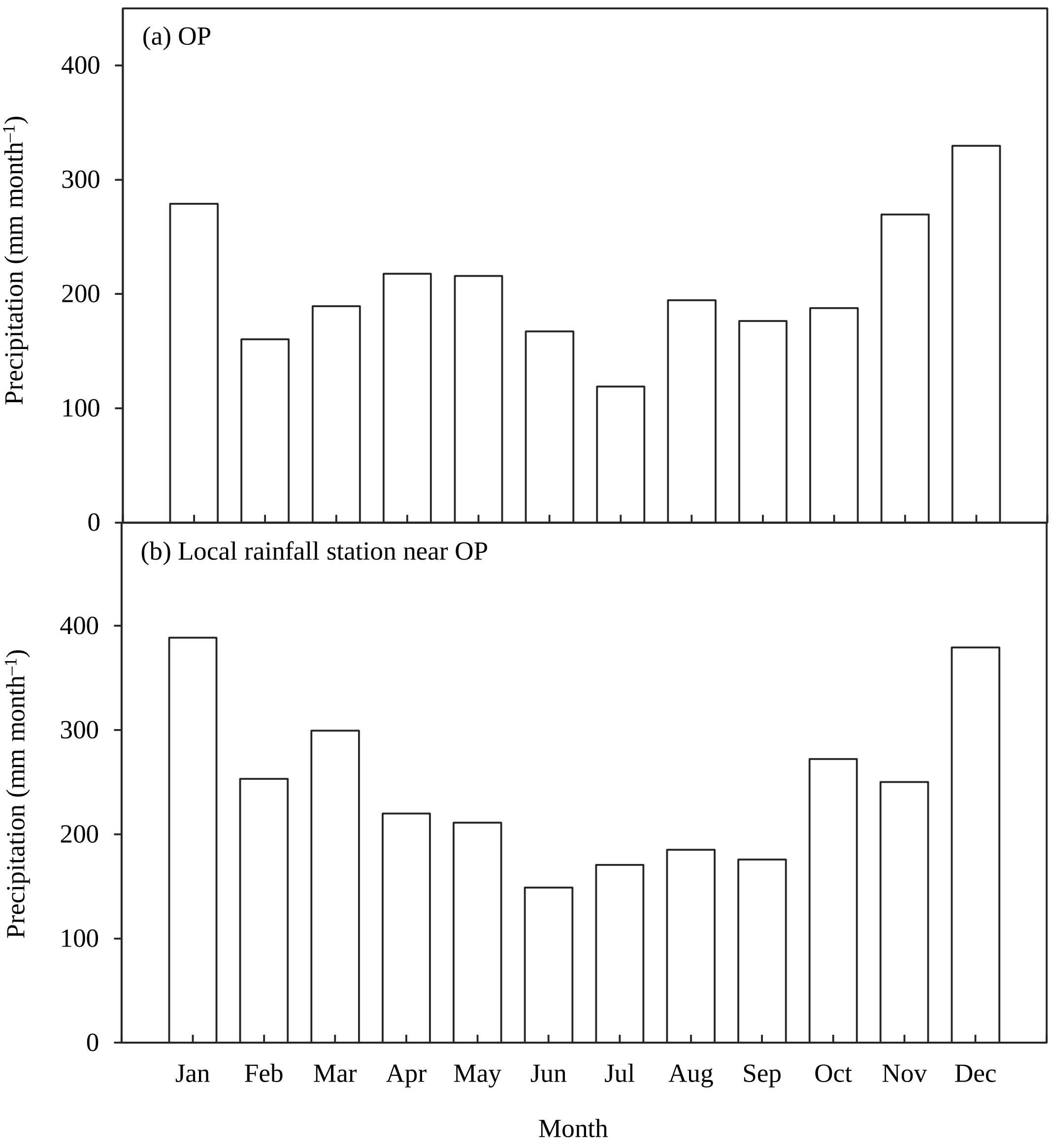


Figure 5.2 Ensemble mean seasonal variations in precipitation at (a) OP (3 years) and (b) local rainfall station near OP (10 years).

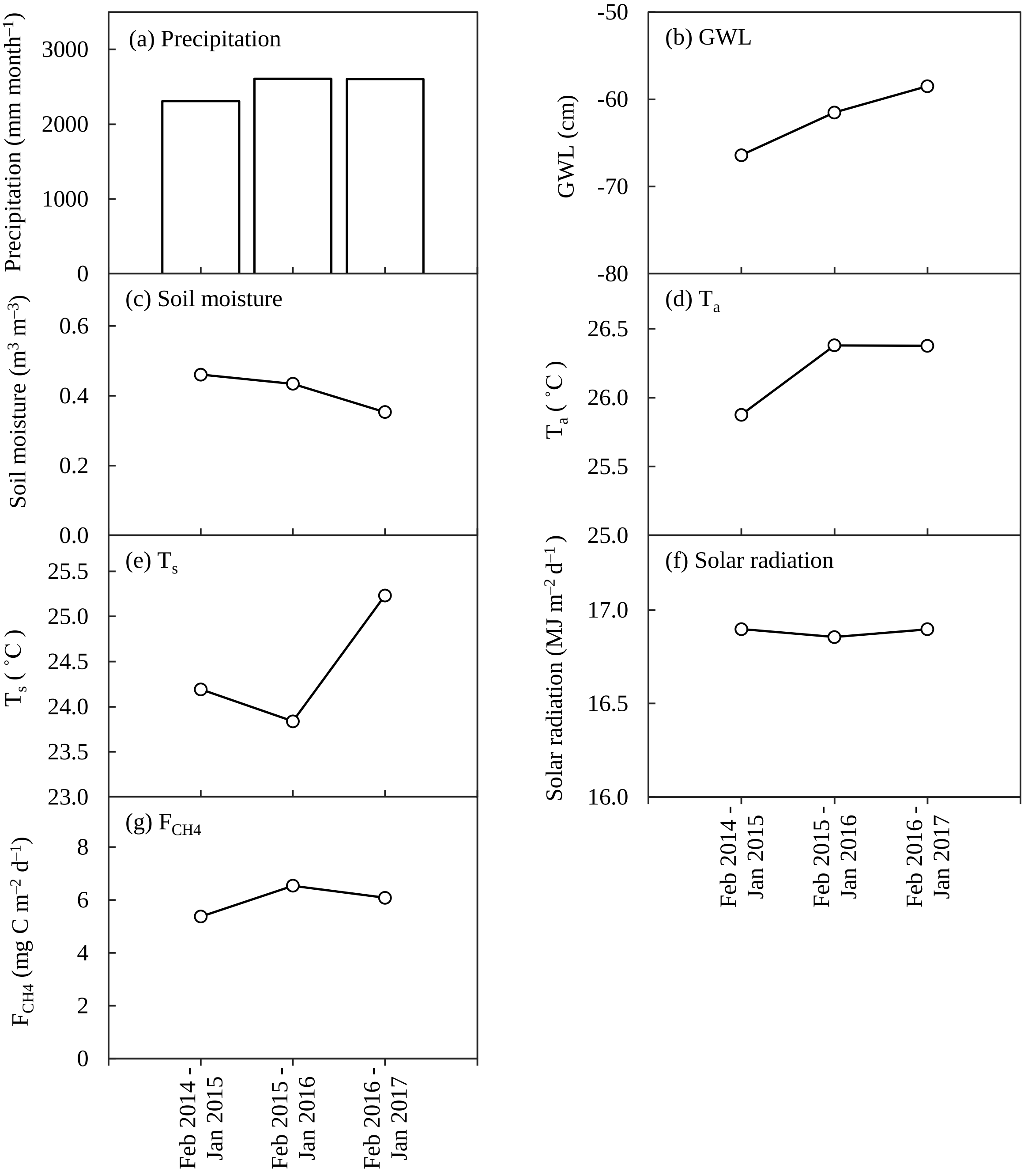


Figure 5.3 Variations in annual (a) precipitation (b) groundwater level (GWL), (c) soil moisture, (d) air temperature (T_a), (e) soil temperature (T_s), (f) solar radiation and (g) gap-filled daily net ecosystem CH_4 exchange (F_{CH4}) from February (Feb) 2014 to January (Jan) 2017.

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}.

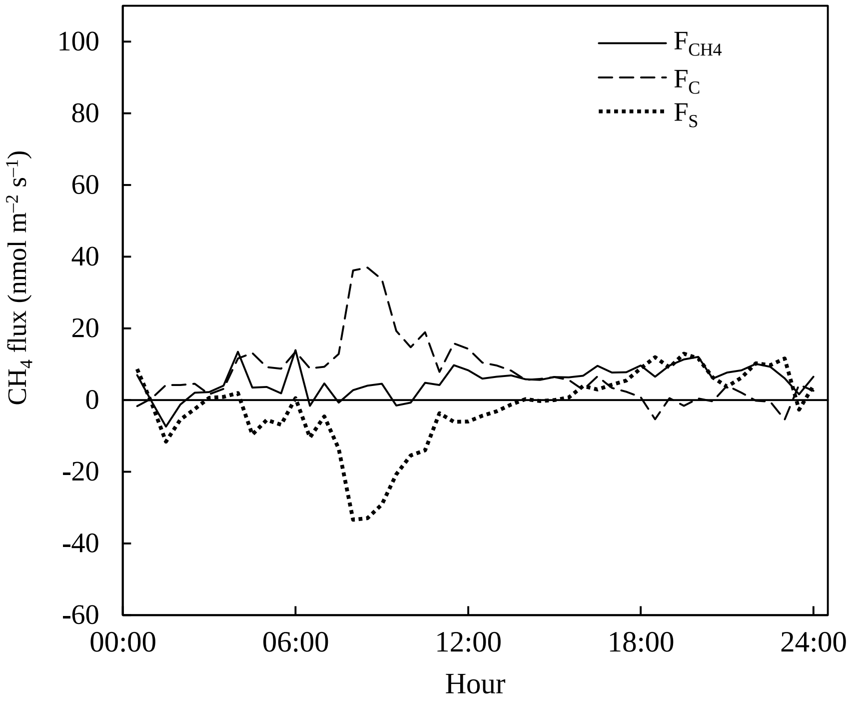


Figure 5.4 Ensemble mean diurnal variations in net ecosystem CH_4 exchange (F_{CH4}), eddy CH_4 flux (F_C) and CH_4 storage change (F_S) from February 2014 to January 2017.

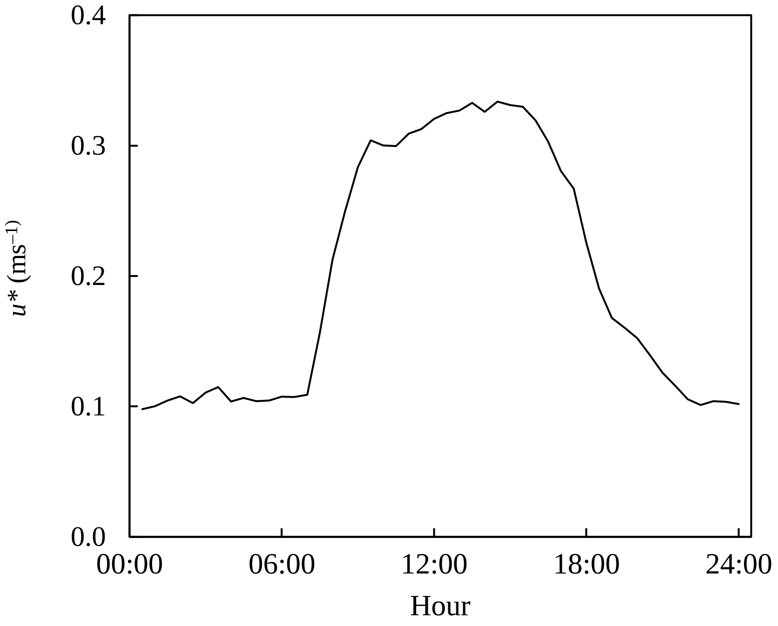


Figure 5.5 Ensemble mean diurnal variations friction velocity (u^*) from February 2014 to January 2017. Increased in turbulent mixing was started at 07:00.

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

Mean of measured half-hourly F_{CH4} (± 1 SD) was 5.8 ± 44.8 nmol m^{-2} s^{-1}, and thus the site was a net CH_4 source. Unexpectedly, gap-filled FCH_4 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_{CH4} to environmental variables

Influences of GWL, soil moisture, T_a and T_s on F_{CH4} 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_{CH4} with GWL, soil moisture and T_s on a daily basis (Fig. 5.6). However, the F_{CH4} was weakly associated with T_a ($R^2 = 0.0111$, $P < 0.05$). Overall, the daily F_{CH4} were cluster around the zero horizontal line.

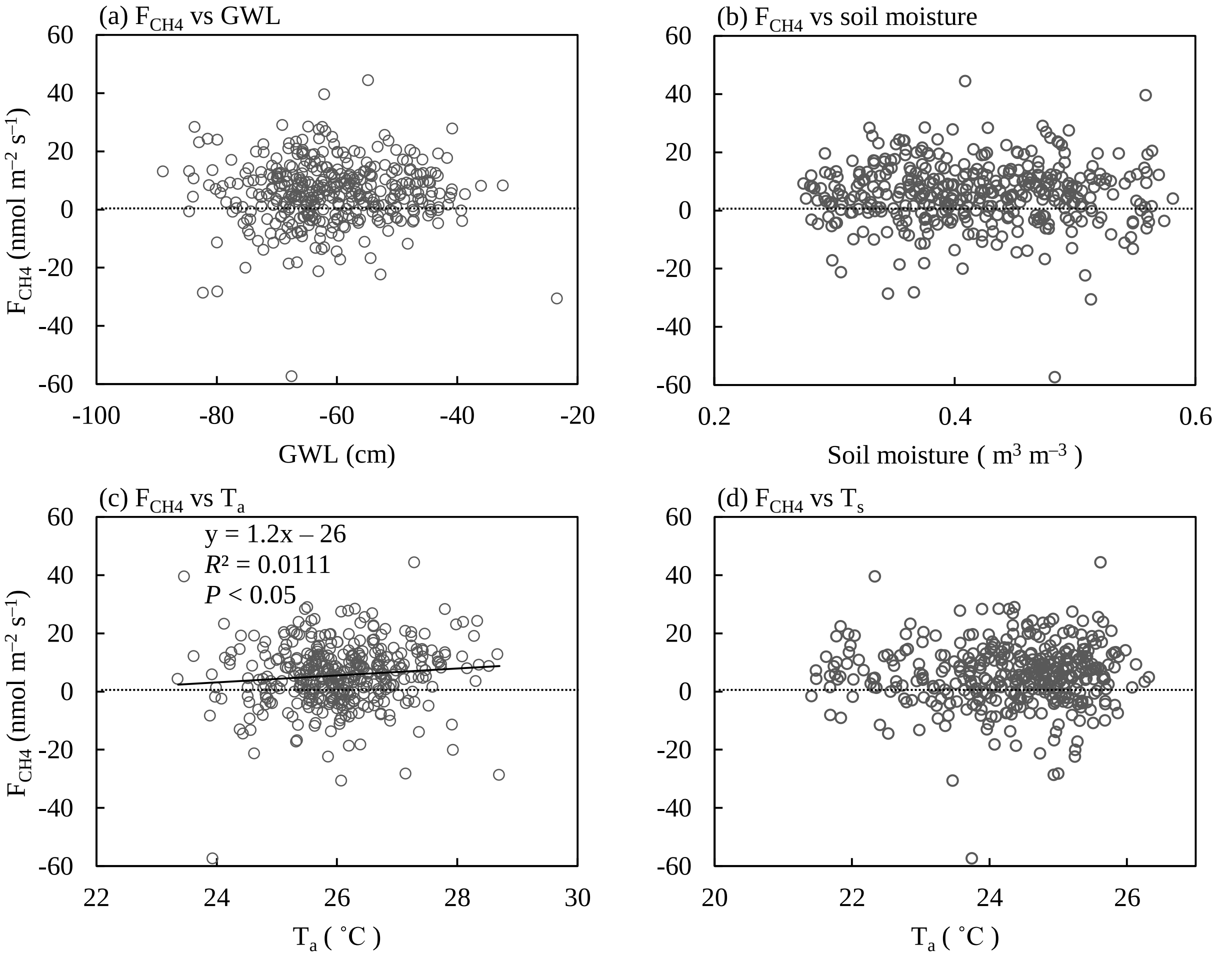


Figure 5.6 Responses of net ecosystem CH_4 exchange (F_{CH4}) to (a) groundwater level (GWL), (b) soil moisture, (c) air temperature (T_a) and (d) soil temperature (T_s) on a daily basis. The relationships were determined using measured data and regression line was drawn.

5.5 Annual CH_4 balance

Annual F_{CH4} (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_{CH4} among the annual period was within 0.42 g C m^{-2} yr^{-1}. Mean annual F_{CH4} (± 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°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 m^2 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 m^2 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).

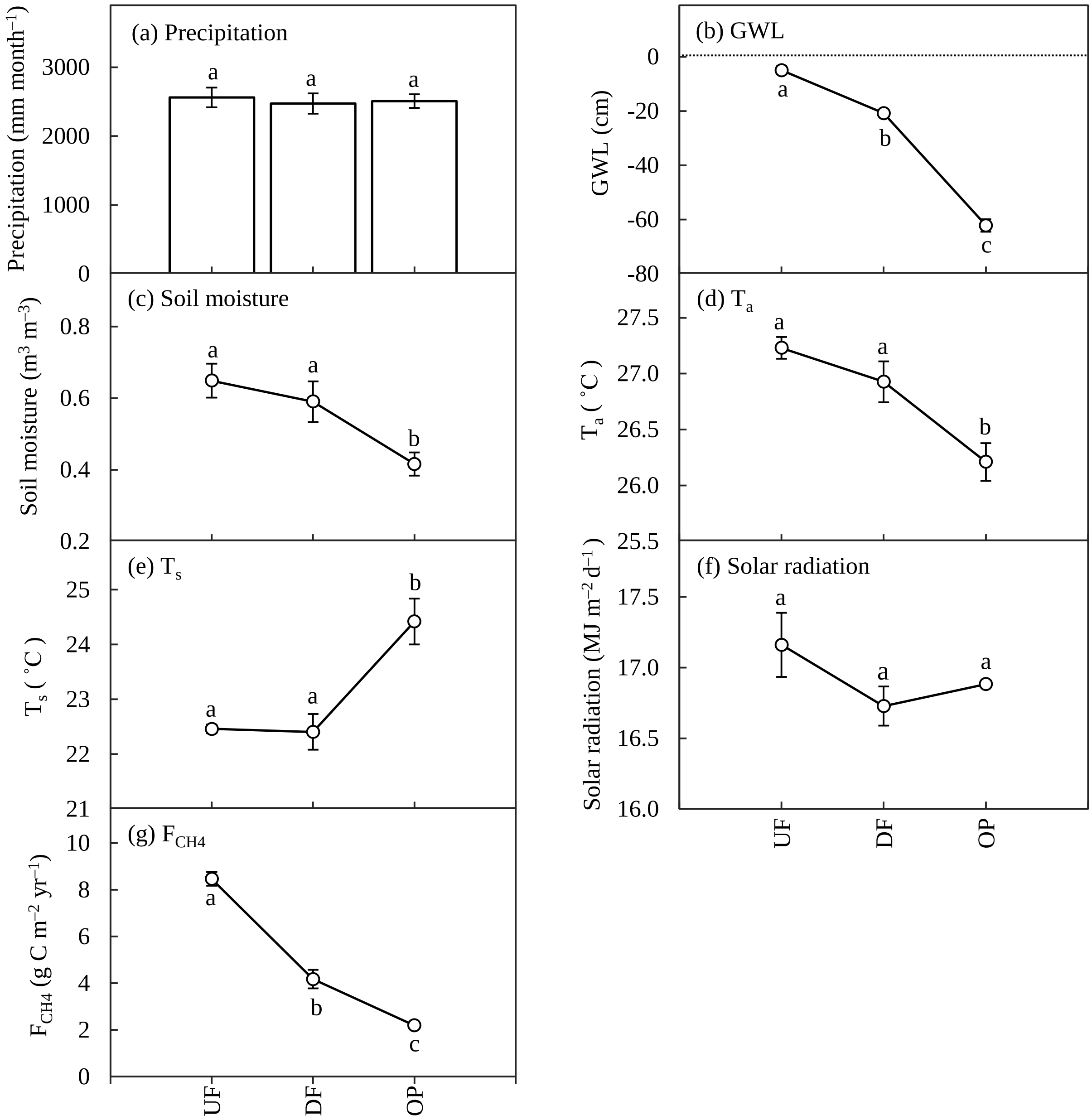


Figure 6.1 Spatial variations in mean annual (a) precipitation (b) groundwater level (GWL), (c) soil moisture, (d) air temperature (T_a), (e) soil temperature (T_s), (f) solar radiation and (g) gap-filled daily net ecosystem CH_4 exchange (F_{CH4}) from February 2014 to January 2017 at UF, DF and OP (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 CH_4 escape to the atmosphere. In contrast, a low GWL promote rapid oxygen diffusion into soil which increase methanotrophy zone, and stimulate CH_4 oxidation (consumption). At UF and DF, highest monthly CH_4 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 CH_4 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 CH_4 emissions in tropical peat. As shown in Figures 3.6a and 4.6a, the F_{CH4} 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 F_{CH4} on GWL (Fig. 5.6a). Some studies on middle latitude peat ecosystems also have reported the influence of GWL on CH_4 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 CH_4 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_{CH4} 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, $P < 0.01$).

Site	Period	Number of days	GWL (cm)	Mean F_{CH4} (nmol m^{-2} s^{-1})
UF	June 2014 (before)	13	–15 to 0	32.6 ± 8.04^a
	September 2014 (after)	17	–15 to 0	10.5 ± 8.77^b
DF	May-June 2015 (before)	42	–20 to –10	12.6 ± 7.76^a
	November-December 2015 (after)	6	–20 to –10	4.17 ± 4.43^b

6.4 Effect of soil moistures, air temperatures (T_a) and soil temperatures (T_s) on F_{CH4}

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_{CH4} (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 has removed the influence of soil moisture on F_{CH4} (Fig. 5.6b).

In middle- and high-lattitude 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-lattitude 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_{CH4} 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_{CH4}. 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-lattitude peatlands (Jackowicz-Korczyński 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_{CH4} 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_{CH4} should be unreal because both T_s and F_{CH4} was controlled by GWL. Increase in GWL will increase the F_{CH4}, but decrease the T_s.

6.5 Inter-site comparison of CH_4 fluxes

There was a significant difference in annual F_{CH4} among the sites ($P < 0.001$; Fig. 6.1f). The mean annual F_{CH4} (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_{CH4} and F_C could be equivalent, because positive and negative values of CH_4 storage change were compensated each other. Similarly with F_{CH4}, the annual eddy CH_4 was significantly different among the sites ($P < 0.001$). The similar annual CH_4 balances obtained independently of $u*$ correction indicate that these tropical peat ecosystems functioned as a net CH_4 source, respectively.

Annual CH_4 emission was largest in UF, followed by DF and OP. To examine the difference among sites, gap-filled F_{CH4} was plotted against GWL on 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 ($P < 0.001$; $R^2 = 0.76$) or an annual ($P < 0.001$; $R^2 = 0.88$) basis. Monthly mean F_{CH4} increased sharply when monthly mean GWL was above –20 cm, and the relationship suggests that F_{CH4} was more than 20 mg C m^{-2} d^{-1} in Sarawak's peat swamp forest when the ground is flooded. On an annual basis, annual F_{CH4} might be 8.03 g C m^{-2} yr^{-1} if annual mean GWL was zero. A similar exponential relationship was reported for annual data of CH_4 flux and GWL from northern peatlands (Abdalla et al., 2016). The significant relationship indicates that the difference in F_{CH4} among the three sits was mainly due to the difference in GWL. Because the GWL of OP was far below the soil surface, the annual CH_4 emission of OP was the lowest out of all sites. Also, the equations would be applicable to estimate CH_4 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 CH_4 to atmosphere. Mean annual GWL of DF was 4.2 times lower than UF. Under lower GWL condition, CH_4 production would have been suppressed while CH_4 oxidation would have been simulated. Consequently, higher oxidation rate (negative flux) was observed at DF. Around 13% of daily F_{CH4} of DF was negative which was much higher than UF with only

3.2 % negative daily F_{CH4} (Table 6.4). There was 27.4 % negative daily F_{CH4} at OP, and it was much higher than UF and DF.

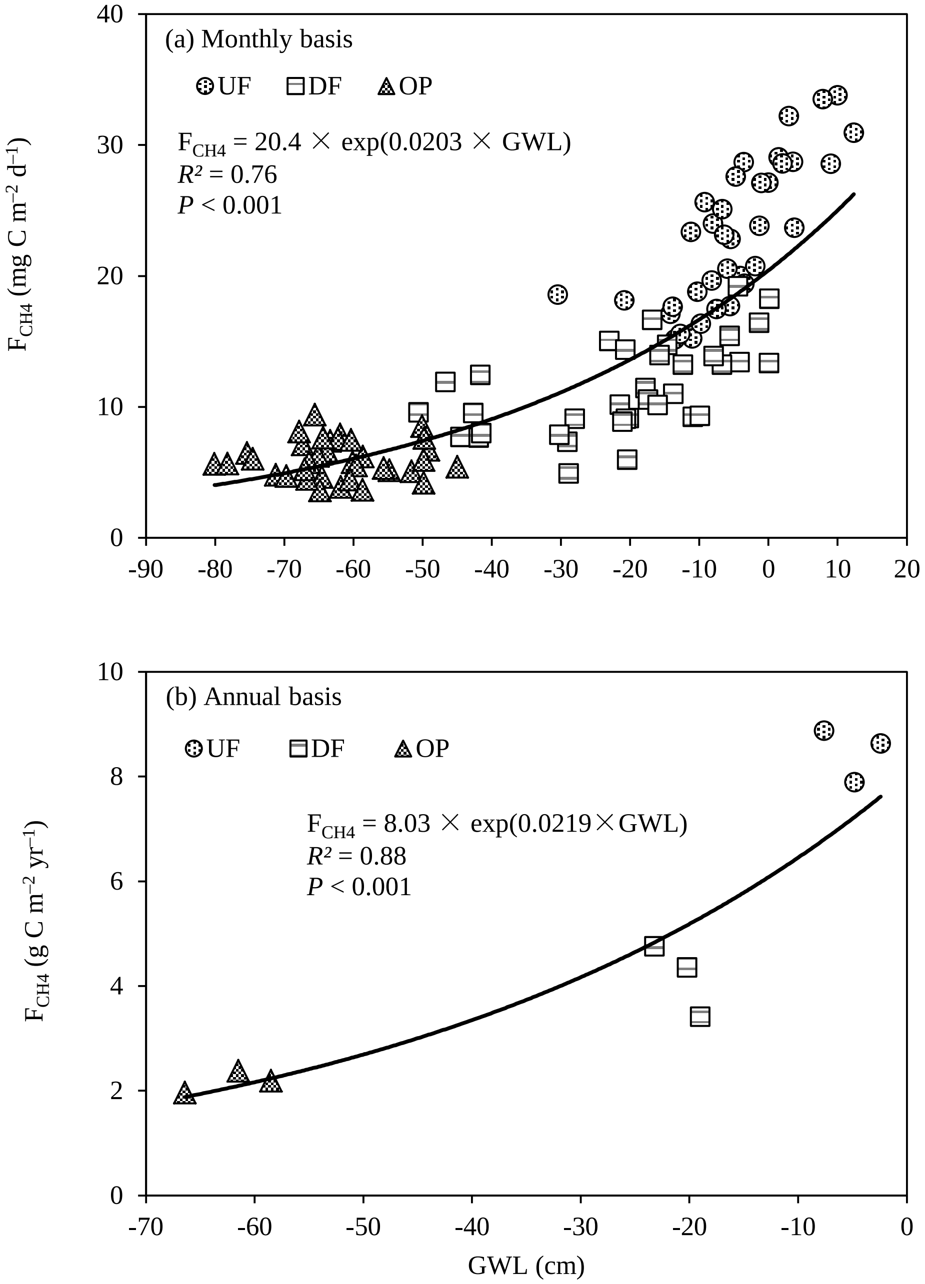


Figure 6.2 Relationships between gap-filled net ecosystem CH_4 exchange (F_{CH4}) and groundwater level (GWL) on (a) monthly basis and (b) annual bases. An exponential curve was significantly fitted.

Table 6.4 Positive and negative daily FCH_4 of UF, DF and OP. Numbers in parentheses indicate the percentages of the data.

Site	Positive FCH_4 (nmol m^{-2} s^{-1})	Negative FCH_4 (nmol m^{-2} s^{-1})
UF	0.10–66.4 (96.8%)	0.10–14.3 (3.2%)
DF	0.02–61.0 (86.9%)	0.38–43.9 (13.1%)
OP	0.09–44.3 (72.6%)	0.07–57.4 (27.4%)

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}.

Annual F_{CH4} 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_{CH4} 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_{CH4} 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_{CH4} 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 6.2 Comparison of annual CH_4 emissions with previous studies on tropical peatlands.

Climate	Location	Technique	Ecosystem	CH_4 emission ($g\ C\ m^{-2}\ yr^{-1}$)	References
Tropical	Sarawak, Malaysia	Eddy covariance	UF • DF • OP ○	7.89 to 8.87 3.41 to 4.35 1.96 to 2.38	This study
Tropical	Sarawak, Malaysia	Eddy covariance	UF •	7.5 to 10.8	Wong et al. (2018)
Tropical	South Kalimantan, Indonesia	Soil static chamber	Secondary forest	1.2	Inubushi et al. (2003)
Tropical	South Kalimantan, Indonesia	Soil static chamber	Secondary forest	4.4	Hadi et al. (2005)
Tropical	Sarawak, Malaysia	Soil static chamber	Mixed peat swamp forest Oil palm plantation ○	0.018 –0.015	Melling et al. (2005b)
Tropical	Central Kalimantan, Indonesia	Soil static chamber	Logged over forest	< 1.02	Jauhiainen et al. (2005)
Tropical	Central Kalimantan, Indonesia	Soil static chamber	Deforested area ○ Drainage-affected selectively logged forest ○	0.148 to 0.205 –0.28 to –0.16	Jauhiainen et al. (2008)
Tropical	Sarawak, Malaysia	Field incubation experiment	Peat samples from Mixed peat swamp, Alan Batu and Alan Bunga forests (in an oil palm plantation ○)	0.113 to 0.253	Sangok et al. (2017)

• 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-Korczyński 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.

Climate	Location	Technique	Ecosystem	CH_4 emission ($g\ C\ m^{-2}\ yr^{-1}$)	References
Tropical	Sarawak, Malaysia	Eddy covariance	UF ● DF ● OP ○	7.89 to 8.87 3.41 to 4.35 1.96 to 2.38	This study
Temperate	Minnesota, USA	Eddy covariance	Poor fen	16.3*	Olson et al. (2013)
Temperate	Qinghai plateau, China	Eddy covariance	Alpine peatland (silty clay loam)	22.6*	Song et al. (2015)
Temperate	Biebrza, Poland	Eddy covariance	River valley fen	18.4*	Fortuniak et al. (2017)
Subarctic	Kaamanen, Finland	Eddy covariance	Aapa mire (fen)	4.1	Hargreaves et al. (2001)
Subarctic	Ruovesi, Finland	Eddy covariance	Oligotrophic fen	9.4	Rinne et al. (2007)
Subarctic	Stordalen, Sweden	Eddy covariance	Mosaic of ombrotrophic and minerotrophic peatlands	20.2*	Jackowicz-Korczyński et al. (2010)
Subarctic	Manitoba, Canada	Eddy covariance	Eutrophic fen	$5.1^{\dagger}$	Hanis et al. (2013)
Arctic	Zackenberg, Greenland	Eddy covariance	Fen	7.1*	Tagesson et al. (2012)
			Mean ± 1 SD	12.9 ± 7.3	

● Undrained peat ecosystem.

○ Drained peat ecosystem.

[*] Mean of different annual periods.

[†] Mean of three gap-filling techniques.

6.8 CH_4 emission sources

Annual F_{CH4} measured by the eddy covariance technique were much larger than the annual soil CH_4 emissions from tropical peatlands (Table 6.2) mainly because the annual F_{CH4} integrate various CH_4 fluxes that were unable captured by soil static chamber. These CH_4 fluxes can be from/to hollow or hummock areas, tree stems, ditches, etc.

It is difficult to determine a spatially-representative soil CH_4 flux by the chamber technique because of uneven microtopography and complex water conditions. For example, soil CH_4 emissions are higher from hollows than hummocks (Pangala et al., 2013). In 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 F_{CH4} in the driest months of UF (July 2014) and DF (June 2014) contributed 7% and 6.5%, respectively, to annual F_{CH4} of 2014. These hollow areas could be hot spots of CH_4 emissions.

It is known that net emission rates of CH_4 are greatly influenced by the transport of CH_4 through herbaceous plants in boreal and temperate peatlands (Waddington et al., 1996; Ding et al., 2003; Frenzel and Karofeld, 2000). Also, tree species growing on waterlogged soils transfer CH_4 produced in the soil and emit the CH_4 from their stems to the atmosphere (Terazawa et al., 2007; Gauci et al., 2010; Rice et al., 2010; Pangala et al., 2013; 2015; 2017). With root systems penetrating anoxic soil horizons, plants transport CH_4 via their aerenchyma to the atmosphere, which bypass zones of aerobic methanotrophy (Bridgham et al., 2013). This process is especially important during the dry season when the unsaturated soil zone is thicker. In Central Kalimantan of Indonesia, CH_4 emission from tree stems was greater than soil surfaces, accounting for 62–87% of total ecosystem CH_4 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 CH_4 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 CH_4 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 CH_4 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 CO_2 and CH_4 for DF. Kiew et al. (2018) reported the annual CO_2 balance of DF from four-year-long eddy flux measurement until 2014. According to their study, DF was a net CO_2 sink of 136 g C m^{-2} yr^{-1}. The annual F_{CH4} of 4.19 g C m^{-2} yr^{-1} can be converted into CO_2 equivalents of 157 g CO_{2e} m^{-2} yr^{-1} (43 g C_CO_2 m^{-2} yr^{-1}) using a GWP factor of 28 (IPCC, 2013). This scaling factor represents the global warming potential for CH_4 over a 100-year time horizon. Thus, the net GWP (CO_2 equivalents) was calculated to be –93 g C $m^{–2}$ $yr^{–1}$ as the sum of –136 (CO_2) and 43 (CH_4) g C m^{-2} yr^{-1}. Consequently, the CH_4 emission decreased the CO_2 sequestration by 32%.

6.10 Effect of land conversion on CH_4 balance

Atmospheric concentration of CH_4 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 ∼53.2 ± 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 CH_4 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 CH_4 flux from a whole ecosystem. This is because the static chamber only consider soil CH_4 flux but not whole-ecosystem CH_4 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 CO_2 balance and the effects on CH_4 balance remains uncertain.

In this study, we measured CH_4 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_{CH4}; examine the diurnal and seasonal variations of F_{CH4}; determine the response of F_{CH4} to GWL; comparison of CH_4 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_{CH4} (± 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_{CH4} was observed at UF.
- At UF and DF, the F_{CH4} 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_{CH4} was positively associated with GWL in UF and DF.
- The F_{CH4} 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_{CH4} of UF, DF and OP were 8.46 ± 0.51, 4.17 ± 0.69 and 2.19 ± 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_{CH4} was significantly different between the ecosystems. The F_{CH4} 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_{CH4} 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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