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Methane fluxes from three ecosystems in tropical peatland of Sarawak, Malaysia

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Abstract

Methane fluxes were measured monthly over a year from tropical peatland of Sarawak, Malaysia using a closed-chamber technique. The CH_4 fluxes in forest ecosystem ranged from -4.53 to 8.40 μg C m^{-2} h^{-1}, in the oil palm ecosystem from -32.78 to 4.17 μg C m^{-2} h^{-1} and in the sago ecosystem from -7.44 to 102.06 μg C m^{-2} h^{-1}. A regression tree approach showed that CH_4 fluxes in each ecosystem were related to different underlying environmental factors. They were relative humidity for forest and water table for both sago and oil palm ecosystems. On an annual basis, both forest and sago were CH_4 source with an emission of 18.34 mg C m^{-2} yr^{-1} for forest and 180 mg C m^{-2} yr^{-1} for sago. Only oil palm ecosystem was a CH_4 sink with an uptake rate of -15.14 mg C m^{-2} yr^{-1}. These results suggest that different dominant underlying environmental factors among the studied ecosystems affected the exchange of CH_4 between tropical peatland and the atmosphere.

Keywords: CH_4; Oil palm; Peatswamp forest; Sago; Tree regression

1. Introduction

Tropical peatland covers an area ranging from 33 to 49 Mha, which is over 8% of the world's total (386–409 Mha) peatland. However, the relatively greater depth of tropical peat allows the storage of more than 70 Gt carbon, which constitutes almost 20% of the global peatland carbon (Maltby and Immirzi, 1993). This carbon store makes it an important source of atmospheric CH_4 (Bartlett and Harriss, 1993) since, the amount of CH_4 in the atmosphere is a balance between CH_4 emission, both natural and anthropogenic, and CH_4 removal (Watson et al., 1990). Tropical peatland is, therefore, commonly considered to play an essential role in the global cycling of carbon and in climate change (Sorenson, 1993).

Methane (CH_4) is a potent greenhouse gas with a relative global warming potential 23 times that of carbon dioxide over a time horizon of 100 years (IPCC, 2001a). The atmospheric CH_4 concentration has doubled, since, the start of the industrial revolution to 1750 ppb in 2000 (IPCC, 2001b).

CH_4 emissions from peat soils to the atmosphere are dependent on the rates of methane production and consumption and the ability of the soil and plants to transport the gas to the surface. Three major environmental factors that control emission rates from peatland were water table position (Crill et al., 1988; Moore and Dalva, 1993; Bartlett and Harriss, 1993), temperature (Crill et al., 1988; Nyakanen et al., 1995), and substrate properties such as pH and mineral nitrogen concentration (Mosier et al., 1991). It has also been suggested that the CH_4 consumption rate depend on management factors such as drainage, compaction and nitrogen (N) fertilization (Hansen et al., 1993; Ball et al., 1997).

Large areas of tropical peatland have been developed in recent years for agricultural plantations in Southeast Asia especially for oil palm and sago whereby drainage is a prerequisite. Drainage may decrease CH_4 flux

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(Martikainen et al., 1992; Flessa et al., 1998) because the lower ground water table may result in a thicker aerobic top layer in the soil, thereby possibly decreasing CH_4 production and increasing CH_4 consumption. Our knowledge of CH_4 fluxes from different ecosystems on tropical peatland is still fragmentary (Bartlett and Harriss, 1993; Smith et al., 2000; Inubushi et al., 2003). Thus, information on the different ecosystems on tropical peatland and their major controlling factors affecting CH_4 fluxes are needed to determine their role as a source or sink of CH_4.

Therefore, this study was conducted with the following objectives: (1) to quantify the amount of CH_4 flux under the forest, sago and oil palm ecosystems and (2) to determine the underlying environmental factors that explain the differences in CH_4 flux in these three ecosystems, particularly the effects of drainage and compaction.

2. Materials and methods

2.1. Sites description

The three experimental sites were all located in the Mukah Division of Sarawak, Malaysia representing three ecosystems namely mixed peat swamp forest, sago (*Metroxylon sagu*) plantation and oil palm (*Elaeis guineensis*) plantation. The main characteristics of these ecosystems are shown in Table 1. The sites were part of a contiguous peat swamp whereby part of it was converted to oil palm plantation and sago plantation. Distance between forest site and oil palm plantation site was about 3.7 km and these sites were about 8.3–11.7 km away from sago plantation site. The climate at the study sites was equatorial characterized by high, even temperatures and heavy rainfall without a distinct dry season.

The peat soils were classified as Typic Tropofibrist in the USDA soil classification system (Soil Survey Staff, 1992) and Fibric Histosols in the FAO classification (FAO-UNESCO, 1974). They were acidic (pH <4.0) with a very high loss of ignition of about 99%. A detailed description of the site properties is provided by Melling et al. (2005).

Measurements of climatic variables and CH_4 emissions were made at monthly intervals from August 2002 to July 2003.

Table 1
Main characteristics of the forest, sago and oil palm ecosystem

Ecosystem	Forest 2°49′N, 111°51′E	Sago 2°45′N, 111°50′E	Oil palm 2°49′N, 111°56′E
Site code	F	S	P
Peat thickness (cm)	480	650	555
Bulk density (g/cm^3)	0.15±0.004	0.16±0.006	0.20±0.007
C:N	27.24±0.96	22.63±0.78	23.43±1.14
Base saturation (%)	22.92±1.68	30.09±2.59	32.32±4.50

The figures show the mean±SE.

2.2. Methane flux measurements

Methane (CH_4) fluxes were determined using a closed-chamber method (Crill, 1991). Three open-bottom stainless steel chambers, 20 cm in diameter and 25 cm in height was placed directly on the soil surface in each site for about 30 min before sampling (Norman et al., 1997) to establish an equilibrium state. The chamber was pushed into the ground by cutting the soil along the edge of the chamber to a depth of 3 cm from the soil surface to avoid gas leakage through the bottom of the chamber by lateral diffusion (Melling et al., 2005). The chambers were sealed with acrylic cover after attaining equilibrium. It had two ports, one for gas sampling and the other for attaching a sampling bag to equilibrate the chamber pressure with the atmospheric pressure. Headspace samples of 20 ml were extracted from the chamber at 0, 10, 20 and 40-min using a polypropylene syringe with a three-way stopcock. The extracted gas was transferred to a 10 ml vacuum vial bottle.

The sampling was conducted between 11.00 and 13.00 h each day.

2.3. Soil gas

Soil gas was sampled using a stainless steel pipe of 9 mm in diameter equipped with a silicon tube and a three-way stopcock inserted to a depth of 5, 10, 20, 40 and 80 cm. The pipes were pushed into the peat with a steel rod inserted in the pipe to prevent physical damage or obstruction during placement. Triplicate measurements were made for each depth. After the pipes were set up, 50 ml of air was siphoned out from each pipe. The pipes were then close by using the three-way stopcock. The pipes were kept overnight to allow the gas concentrations in the pipes to equilibrate with the soil air. Thus, the pipes were installed a day before sampling. From each pipe, 50 ml of the soil gas were extracted to a Tedlar bag using a polypropylene syringe whereby 20 ml was transferred into a 10 ml vacuum vial bottle using a double-ended hypodermic needle.

If only water samples were extracted from the pipes, dissolved CH_4 concentrations were measured using the methods of McAullife (1971). Using a 60 ml syringe, 30 ml water samples were extracted from the pipe, and then 30 ml of air was immediately drawn into the syringe. The syringe was shaken vigorously for 3 min and a 20 ml headspace sample was then transferred to a 10 ml vacuum vial bottle. Extraction of CH_4 by this method was 98% efficient. Soil pore space air and water samples were collected in each site at the time of flux measurements.

2.4. Methane analysis

CH_4 concentration was determined by a gas chromatograph equipped with a flame ionization detector (Hewlett Packard 6890N) maintained at 250 °C, using a 2 m long Porapak N column (80/100 mesh) maintained at 50 °C with

a N_2 carrier gas flowing at 40 ml min^{-1}. CH_4 fluxes were calculated from the linear increase or decrease in gas concentration in the chamber with time, using a linear regression equation (Christensen et al., 1995). The annual CH_4 fluxes were calculated from the monthly averages as follows:

$$\text{Cumulative gas flux} = \sum_{i=1}^{n} R_i D_i$$

where R_i is the mean gas flux (g m^{-2} d^{-1}) of the two sampling times, D_i is the number of days in the sampling interval, and n is the number of sampling times. In this study, negative fluxes indicated the uptake of atmospheric CH_4, while positive fluxes indicated the net production of CH_4 from the peat soil.

2.5. Environmental variables

Air temperature, soil temperatures at 5 and 10 cm below the soil surface, relative humidity (RH) and the gaseous flux were measured at the same time. Water table depth was also recorded when the CH_4 flux was measured. Monthly precipitation in each ecosystem was recorded. Three soil samples were collected monthly from each ecosystem at the same time as gas samplings were bulked for both physical and chemical analysis. Three other undisturbed core samples were also taken to determine their bulk density and moisture content. Details of the measurements have already been described by Melling et al. (2005).

2.6. Statistical analysis

Repeated measure analysis was used to compare methane fluxes with ecosystems as the subject and time as repeated measure using GenStat (GenStat, 2002). Tree regression was used instead of the classical multiple linear regression to avoid multicolinearity problem between the independent variables.

Tree regression is a non-parametric, non-monotonic, and non-linear exploratory data analysis technique for uncovering structure in the data (Clark and Pregibon, 1992), which allows the nesting of variables that predict gas fluxes (Melling et al., 2005). This technique develops a decision tree based on a binary partitioning algorithm that divides data in a recursive manner until each group is either homogenous or contain a user-defined minimum number of observations. At each split, the algorithm considers each explanatory variable and chooses the one that results in the greatest reduction in deviance. This approach usually creates an overly complex decision tree that needs to be pruned in order to convey the most important information i.e. the nodes that explain the largest amount of deviance (Breiman et al., 1993). The advantage of regression trees is the transparency of results, and the relative importance of inputs can be easily assessed. Regression trees are generally regarded as superior to standard regression with respect to capturing interactions and non-addictive behavior (Mathsoft, 1999). The tree regression analysis was performed using S-PLUS 2000 (Mathsoft, 1999).

3. Results

3.1. Environmental variables

The mean air temperatures in the forest, sago and oil palm ecosystems were 27.4±0.19, 33.0±0.42 and 30.9±0.35 °C, respectively. The mean soil temperatures at 5 cm for sago and oil palm ecosystems were about 28.2±0.19 and 28.0±0.17 °C, respectively, whilst the forest showed a lower mean temperature of 25.9±0.11 °C. For soil temperature at 10 cm, the forest also showed the lowest temperature of 26.0±0.10 °C followed by sago at 27.1±0.08 °C and oil palm at 27.6±0.14 °C.

The rainfall and water table patterns in the three ecosystems also followed a similar seasonal variation with the highest recorded in January at all sites (Fig. 1a and b). The monthly rainfall in the forest, sago and oil palm ecosystems ranged from 33–418, 37–610 and 43–537 mm, respectively. The highest mean water table in the sago ecosystem was 27.4 cm compared with 45.3 cm in forest and 60.2 cm in oil palm ecosystem.

Similarly, soil water-filled pore space (WFPS) was the highest in sago ecosystem with a mean of 78.1% compared with 57.6 and 60.4% in forest and oil palm ecosystem, respectively (Fig. 1c). In contrast, RH was highest in the forest followed by oil palm and sago ecosystems. Their monthly RH ranges from 70–99, 43–85 and 48–77%, respectively (Fig. 1d).

3.2. Methane flux

The monthly CH_4 fluxes varied significantly between the three ecosystems (Table 2). The seasonal variation in CH_4 fluxes in forest and oil palm ecosystems did not follow the measured climatic and environmental variables whereas in sago ecosystem, it correlated with the monthly rainfall ($r=0.73$) and depth of water table ($r=0.73$) (Figs. 2 and 3).

Both CH_4 emission and uptake were observed in all the three ecosystems. The CH_4 fluxes in forest ecosystem ranged from −4.53 to 8.40 μg C m^{-2} h^{-1}, oil palm ecosystem −32.78 to 4.17 μg C m^{-2} h^{-1} and sago ecosystem −7.44 to 102.06 μg C m^{-2} h^{-1}. The highest CH_4 emission rate in forest ecosystem was recorded in December 2002 and a month later in oil palm and sago ecosystems. The highest CH_4 uptake rates were recorded in different months being February 2003, August 2002 and December 2002 for forest, oil palm and sago ecosystem, respectively.

The repeated measure analysis showed that ecosystem, time and ecosystem×time were significantly different (Table 2). Annually, both forest and sago ecosystems were

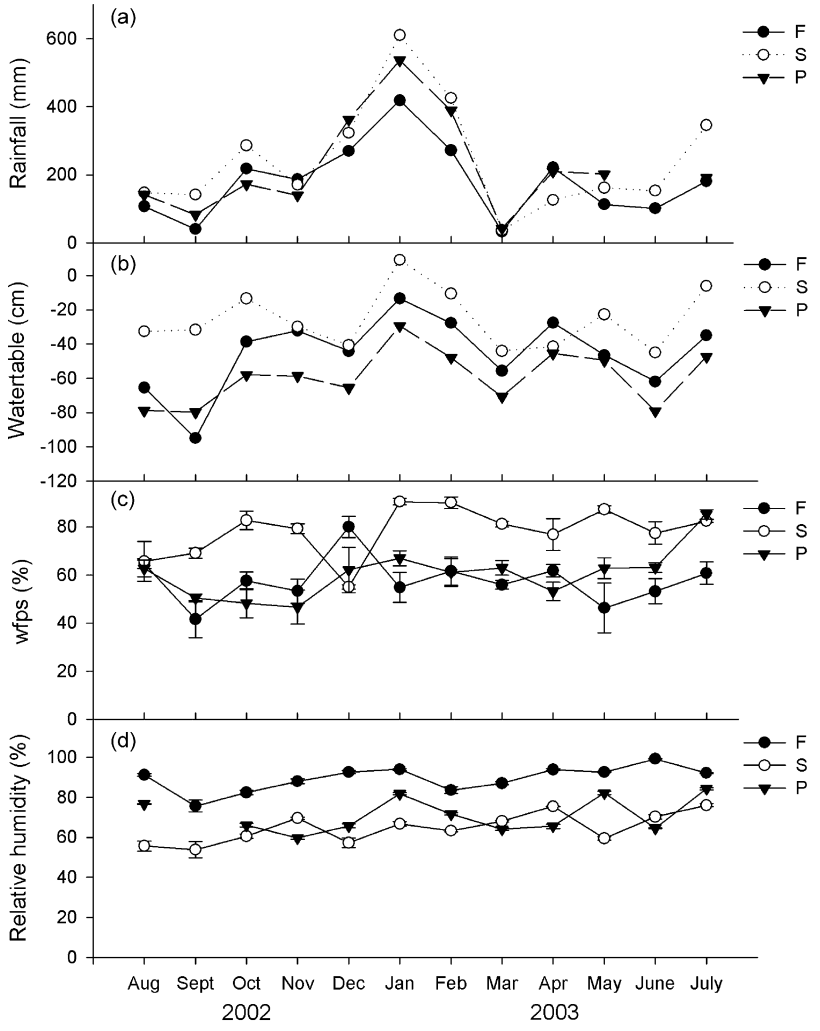

Fig. 1. Rainfall (a), watertable (b), water-filled pore space (c), and relative humidity (d). Data represent means ± SE ($n = 3$). Error bars indicate SE of the mean. Symbols without error bars have errors smaller than the symbols.

CH_4 sources (Table 2) with sago ecosystem producing an order higher than forest. The oil palm ecosystem was a CH_4 sink with an uptake rate of 15 mg C m^{-2} yr^{-1}.

3.3. Soil gas concentrations

The mean annual concentrations of CH_4 in the air above soil surface were 2.28 ± 0.08 ppm for forest, 2.21 ± 0.05 ppm for sago and 2.32 ± 0.08 ppm for oil palm ecosystem (Fig. 3a–c). Depth profiles of soil CH_4 concentrations in forest and oil palm ecosystems had similar patterns at all sampling dates (Fig. 3a and b). Both have discontinuities in CH_4 gradients at approximately 20 cm depth. The soil air CH_4 concentrations in the sago ecosystem increased throughout the depth profile (Fig. 3b). The highest soil CH_4 concentration for all the ecosystems occurred at 80 cm depth but in the forest ecosystem, it was only 33.7 ± 7.0 ppm compared with 1086 ± 123.2 and 1465 ± 309.9 ppm in sago and oil palm ecosystems respectively.

3.4. Regression trees

The regression tree method selected RH, water table and WFPS as predictor variables for CH_4 flux in forest ecosystem (Fig. 4). The RH was the most important splitting variable in determining the CH_4 uptake and emission; the critical value being 90.55%. The highest mean CH_4 emission of 9.23 μg C m^{-2} h^{-1} occurred when the RH

Table 2
Soil CH_4 flux and cumulative flux for forest, sago and oil palm ecosystem

Ecosystem	Methane flux, μg C m^{-2} h^{-1}	Cumulative flux, mg C m^{-2} yr^{-1}
Forest	2.27 ± 1.37	18.34
Sago	22.06 ± 5.68	179.54
Oil palm	−3.58 ± 2.28	−15.14

Note: (a) The p-value for ecosystem was 0.005. The SE of differences of means for ecosystem was 4.91. (b) The p-value for time was 0.05. The SE of differences of means for time was 7.51. (c) The p-value for ecosystem × time was 0.047. The SE of differences of means for ecosystem × time was 13.38.

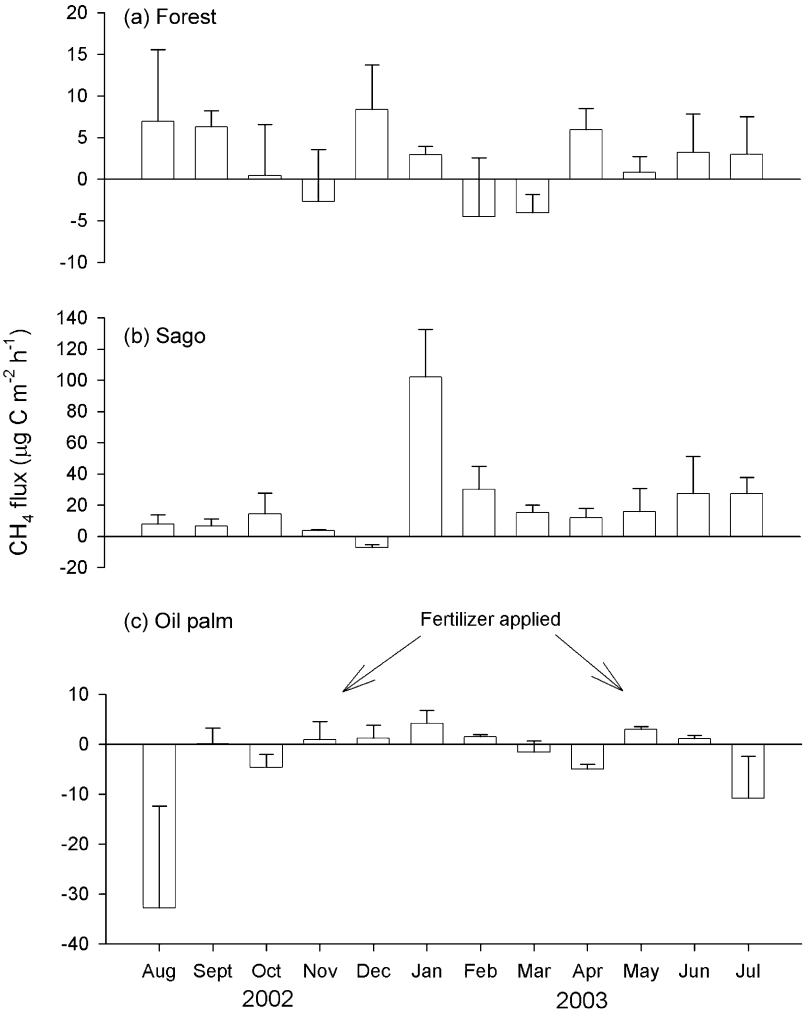

Fig. 2. Monthly methane flux (µg C m^{-2} h^{-1}) at the forest, sago and oil palm ecosystem. Data represent means ± SE ($n=3$). Error bars indicate SE of the mean. Symbols without error bars have errors smaller than the symbols.

was more than 90.55% and water table more than 49 cm. The highest mean CH_4 uptake of 5.42 µg C m^{-2} h^{-1} occurred when the RH was less than 90.55%, and WFPS more than 54.38%.

Unlike the forest ecosystems, water table, soil temperature at 10 cm and WFPS were chosen as the predictor variables in the sago ecosystem (Fig. 5). The first split for the CH_4 flux in the sago ecosystem was water table with

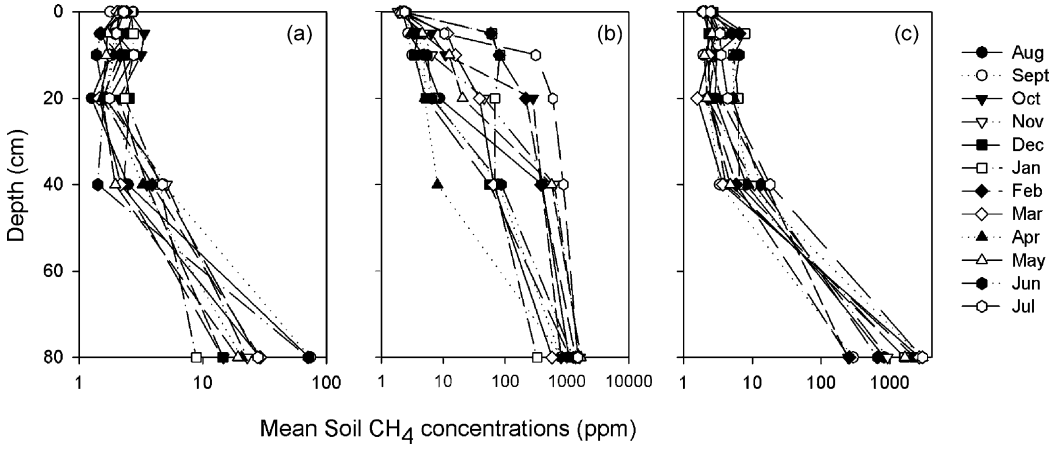

Fig. 3. Mean soil profile CH_4 concentration (ppm) of forest (a), sago (b) and oil palm (c) ecosystem.

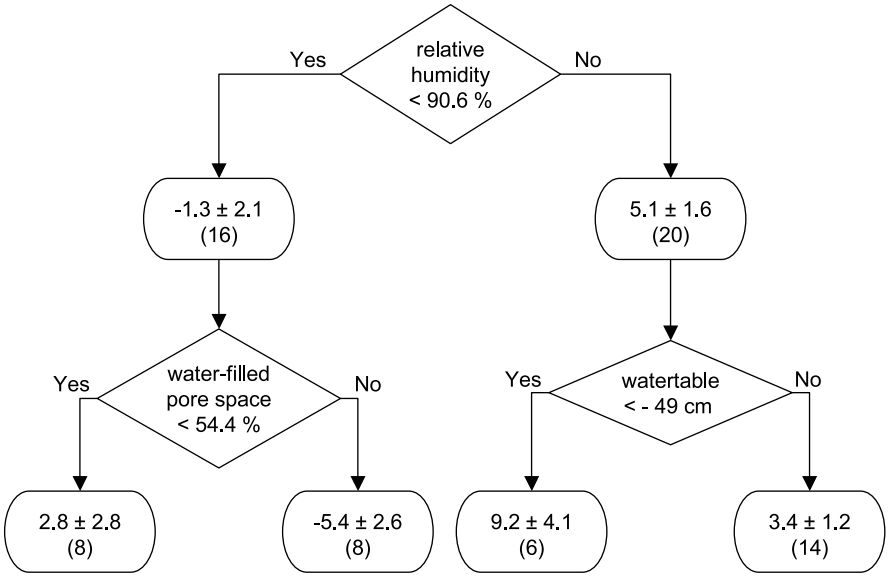

Fig. 4. Regression tree for forest ecosystem ($R^2 = 0.33$). The CH_4 flux ($\mu g\ C\ m^{-2}\ h^{-1}$) in the group is shown in each box. Values are means ± SE. The number in bracket is the count of samples in the group.

a critical value of 17.2 cm. The highest mean CH_4 emission of 78.7 $\mu g\ C\ m^{-2}\ h^{-1}$ occurred when the water table was less than 17.2 cm and WFPS greater than 87.6%. On the other hand, water table more than 17.2 cm and soil temperature at 10 cm less than 27.3 °C resulted in the lowest CH_4 emission of 1.7 $\mu g\ C\ m^{-2}\ h^{-1}$.

For the oil palm ecosystem, water table, WFPS and soil temperature at 5 cm were chosen as the predictor variables (Fig. 6). Water table was used to separate between low and high CH_4 uptake with critical value at 77.4 cm. The highest mean CH_4 uptake of 17.44 $\mu g\ C\ m^{-2}\ h^{-1}$ occurred when the water table was more than 77.4 cm. Highest mean CH_4 emission of 1.13 $\mu g\ C\ m^{-2}\ h^{-1}$ occurred when the water table was less than 77.4 cm, WFPS less than 72.5% and soil temperature at 5 cm less than 29 °C.

4. Discussion

4.1. Methane flux and soil gas concentrations

No distinct seasonal variation was observed in the methane flux in both the forest and oil palm ecosystems even though precipitation and water table depth were

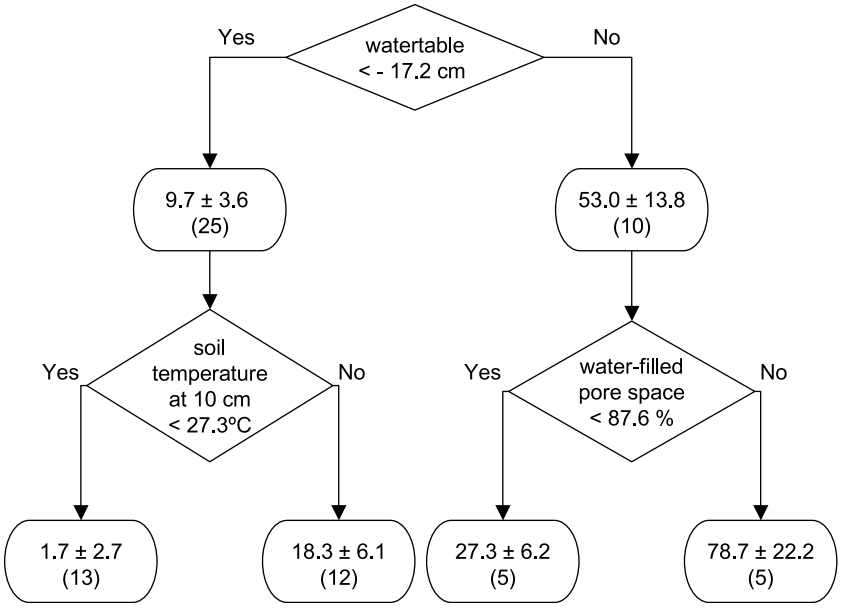

Fig. 5. Regression tree for sago ecosystem ($R^2 = 0.57$). The CH_4 flux ($\mu g\ C\ m^{-2}\ h^{-1}$) in the group is shown in each box. Values are means ± SE. The number in bracket is the count of samples in the group.

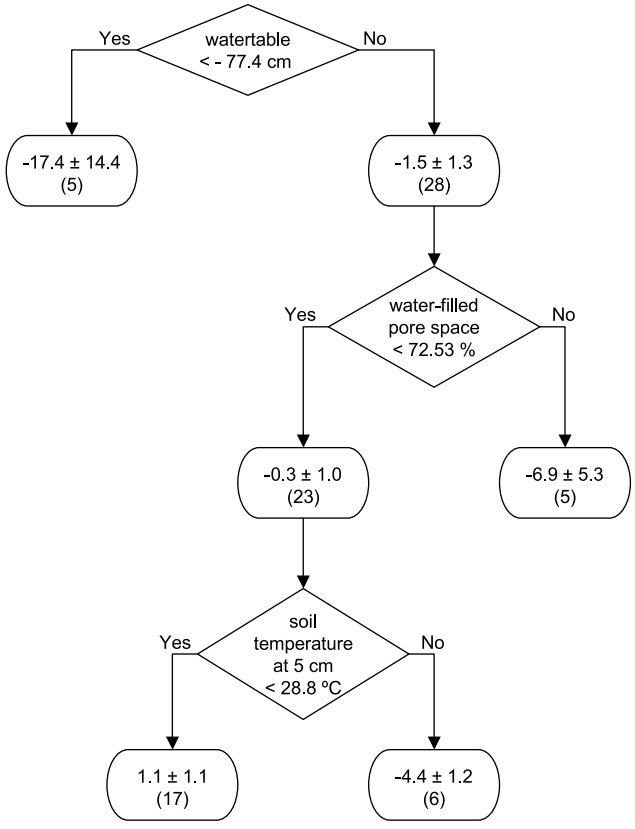

Fig. 6. Regression tree for oil palm ecosystem ($R^2 = 0.22$). The CH_4 flux ($\mu g\ C\ m^{-2}\ h^{-1}$) in the group is shown in each box. Values are means ± SE. The number in bracket is the count of samples in the group.

observed to have distinct seasonal variation. However, in the sago ecosystem, the seasonal variation in CH_4 flux was positively correlated with rainfall due to the necessary retention of high water table for the crop which increased its susceptibility to flooding (and anaerobic conditions) as shown in January 2003 resulting in high CH_4 emission (Fig. 2).

Using the regression tree approach, we found that different dominant predictor environmental variables had influenced the variations in CH_4 flux in each ecosystem. They were RH for forest (Fig. 4) and water table for both sago (Fig. 5) and oil palm ecosystems (Fig. 6).

Although, RH was well correlated with rainfall and water table, it showed a larger monthly fluctuation indicating its higher sensitivity to environmental changes. It probably had an indirect effect, since, it was associated with high water table and WFPS resulting in larger CH_4 production and emission. RH had no significant effect on CH_4 fluxes in oil palm and sago ecosystems probably due to their more open canopies resulting in lower RH and poorer correlation with water table and WFPS.

Water table was the most important environmental variable that controlled CH_4 fluxes in both the sago and oil palm ecosystems (Figs. 5 and 6), which was agreeable with other researchers (Moore and Dalva, 1993; Martikainen et al., 1992). In fact, the largest monthly averaged CH_4 emission rates were observed in January 2003 for both sago and oil palm ecosystems when the highest water table was measured at the sites, which probably caused an anoxic condition that was essential for methanogenesis. In the oil palm ecosystem, the water table was also used to separate high and low CH_4 uptake where low water table depth generally resulted in the former (Fig. 6). This might be attributed to the thicker aerobic layer with lower water table, which probably increased the oxidation of CH_4.

When the WFPS was very high (>87.6%) as in the sago ecosystem (Fig. 5), high CH_4 emission occurred probably due to high process of methanogenesis. Under the forest and oil palm ecosystem, where the upper horizons were more aerobic, the increase in WFPS may probably have facilitate CH_4 consumption resulting in CH_4 uptake. In the sago ecosystem, an increase in temperature would increase CH_4 emission due to higher gas diffusion rate. However, in the oil palm ecosystem, which has a thick aerobic layer, the higher temperature probably also had increased CH_4 oxidation resulting in higher CH_4 uptake.

Upon cultivation of sago and oil palm on tropical peatland, the CH_4 gas concentration had increased more than 10-fold as shown at 80 cm depth (Fig. 3a–c). This might be ascribed to the increased in soil temperature and decomposition rate as indicated by the lower C:N ratio (Table 1) after land conversion.

The marked increase in CH_4 gas concentration with deeper soil depth (Fig. 3a–c) was probably an interaction of higher WFPS and greater anaerobicity, CH_4 diffusion rate through the peat profile, and CH_4 emission rate. In forest and oil palm ecosystems where CH_4 emissions were not dominant, there were clear declines in CH_4 gas concentrations at 20 cm depth due to diffusion and CH_4 consumption. In the sago ecosystem where CH_4 emissions were dominant, clear CH_4 gradients were observed above 20 cm depth only. This indicated a slow diffusion of CH_4 from the lower depth probably due to high water table.

4.2. Effect of types of ecosystem on CH_4 flux

CH_4 fluxes from the three ecosystems on tropical peatland showed high variation, both temporally and spatially. This has also been reported by Waddington and Roulet (1996), Turetsky et al. (2002) and Inubushi et al. (2003) for different types of peat ecosystem in both temperate and tropical regions. The CH_4 fluxes for forest with a range of -4.53 to 8.40 $\mu g\ C\ m^{-2}\ h^{-1}$ were similar to grassland on peat in Netherlands (van den Pol-van Dasselar et al., 1997). The annual soil CH_4 emission of 18.34 $mg\ C\ m^{-2}\ yr^{-1}$ for the forest ecosystem, 179.54 $mg\ C\ m^{-2}\ yr^{-1}$ for the sago ecosystem and $-15.14\ mg\ C\ m^{-2}\ yr^{-1}$ for oil palm ecosystem (Table 2) were similar to those observed by other researchers (Jauhiainen et al., 2001; Morishita, Unpublished) but they

were very much lower than those reported by Bartlett and Harriss (1993) and Inubushi et al. (2003).

Forest had a well-developed soil structure and a more permeable surface layer whereby it can easily emit CH_4. This was supported by the slight increases in CH_4 concentration with depth indicating high gas permeability (Fig. 3a). The low water table in the forest probably contributed to the minimal CH_4 flux to the atmosphere because CH_4 produced at depth was oxidized as it diffused upward through the aerobic surface peat layers (Roulet and Moore, 1995; Turetsky et al., 2002).

Upon cultivation to sago, the annual CH_4 emission increased to 179.54 mg C m^{-2} yr^{-1} which was similar to the unfertilized grassland (Glatzel and Stahr, 2001). This shift from a low to a high CH_4 emission might be attributed to the well controlled, high water table, which enhanced the potential for high rates of methanogenesis and CH_4 emissions. Furthermore, higher temperature and low C:N ratio (Table 1) would also contribute to the higher rates of methanogenesis and CH_4 emissions.

The cultivation of tropical peatland primary forest to oil palm promoted CH_4 oxidation due to the lowering of water table by drainage which increased the thickness of aerobic soil layer. This improved CH_4 uptake making the oil palm ecosystem a CH_4 sink. Similar results have also been reported for soils drained for agriculture, which were generally attributed to the reduced CH_4 fluxes and higher CH_4 oxidation (Crill et al., 1988; Roulet and Moore, 1995; Nyakanen et al., 1995; Maljanen et al., 2003).

Drainage and compaction in the oil palm ecosystem had also increased the soil bulk density by 33% (Table 1), thus reducing the diffusion of CH_4 and oxygen (Ball et al., 1997). Hansen et al. (1993) also reported that compaction of agricultural soil can reduce CH_4 uptake by 52% due to above reasons. The higher bulk density would similarly increase the micropores resulting in an increase in moisture retention and probably the amount of anaerobic sites even at lower water content. These anaerobic sites had stimulated the increase in CH_4 production but with the reduced CH_4 diffusion, led to a higher accumulation of soil gas concentration as compared to the forest ecosystem (Fig. 3a and c).

The positive effects of water table and compaction on CH_4 emission in tropical peatland are also found in the boreal and temperate zones.

5. Conclusion

The underlying environmental factors that cause the variations in CH_4 flux between the three peatland ecosystems in Sarawak, Malaysia differed significantly being RH in forest ecosystem and water table in oil palm and sago ecosystems. The conversion of tropical forest on peat to sago increased CH_4 emission by 10-fold due to the necessary retention of high water table. Conversely, its conversion to oil palm resulted in CH_4 uptake which might be attributed to the lowering of water table and soil compaction. These results have important implications for land-use planning and agricultural management on tropical peatland especially to minimize the adverse effects of human activity on CH_4 emission to the atmosphere.

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