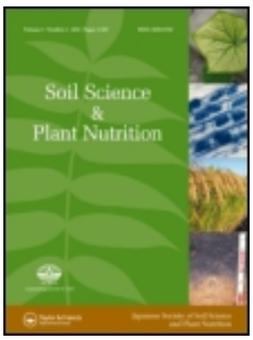

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ORIGINAL ARTICLE

Short-term effect of urea on CH_4 flux under the oil palm (*Elaeis guineensis*) on tropical peatland in Sarawak, Malaysia

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Abstract

Methane flux was measured monthly from August 2002 to July 2003 at an oil palm plantation on tropical peatland in Sarawak, Malaysia, using a closed chamber technique. Urea was applied twice, once in November 2002 and once in May 2003. The monthly CH_4 flux ranged from –32.78 to 4.17 μg C m^{-2} h^{-1}. Urea applications increased CH_4 emissions in the month of application and emissions remained slightly higher a month later before the effect disappeared in the third month after application (i.e. back to CH_4 uptake). This effect was the result of increased soil NH_4^+ content that was not immediately absorbed by the oil palm following urea application, which reduced the oxidation of CH_4, resulting in its enhanced emission. By using the Cate–Nelson linear-plateau model, the critical soil NH_4^+ content causing CH_4 emissions in the oil palm ecosystem was 42.75 mg kg^{-1} soil. However, the inhibitory effect of NH_4^+ on the oxidation of CH_4 was mitigated by low rainfall and the pyrophosphate solubility index (PSI), where the former might increase oxidation of CH_4 and the latter was a reflection of the low soluble substrate for methane production. Thus, the splitting and timing of urea applications are important not only to optimize oil palm yield, but also to reduce soil NH_4^+ content to minimize CH_4 emissions and, therefore, its potential negative impact on the environment.

Key words: Cate–Nelson linear-plateau model, greenhouse gas, methane, NH_4^+, oil palm.

INTRODUCTION

Tropical peatland as a wetland could be an important source and sink of atmospheric methane (CH_4). Tropical peatland constitutes over 8% of the global peatland area, but may store more than 20% of the global peatland carbon. Therefore, it is commonly considered to play an essential role in the global cycling of carbon and in climate change (Sorenson 1993).

Since the start of the industrial revolution, atmospheric CH_4 concentration has doubled to 1750 p.p.b. in 2000 (Intergovernmental Panel on Climate Change 2001). Anthropogenic sources contribute to approximately 70% of CH_4 production and the balance comes from natural sources (Intergovernmental Panel on Climate Change 1992). Globally, agriculture is considered to be responsible for approximately two-thirds of the anthropogenic sources. CH_4 fluxes 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 CH_4 emission rates from peatland are water table position, temperature and substrate properties such as pH and mineral nitrogen content (Barlett and Harriss 1993; Crill *et al.* 1988; Moore and Dalva 1993). It has also been suggested that the CH_4 consumption rate depends on management factors such as drainage, compaction and nitrogen (N) fertilization (Ball *et al.* 1997; Born *et al.* 1990; Hansen *et al.* 1993; Keller *et al.* 1990, 1993; Mosier *et al.* 1991; Weitz *et al.* 1998).

Recently, large areas of tropical peatland in South-East Asia have been developed for large-scale agricultural plantations, particularly for oil palm to which large quantities of urea were applied. However, the impact of urea on CH_4 emission under oil palm has not been investigated. Thus, the objectives of this study were to quantify the effect of urea on seasonal CH_4 variation and to determine the environmental factors controlling it.

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Table 1 Environmental characteristics of the study site

Characteristics	Mean ± standar error
Peat thickness (cm)	555
Humification value†	H3–H5
Bulk density (g cm^{-3})	0.20 ± 0.007
Mean monthly air temperature (°C)	30.9 ± 0.35
Mean monthly soil temperature at 5 cm (°C)	28.0 ± 0.17
Mean monthly soil temperature at 10 cm (°C)	27.6 ± 0.14
Annual rainfall (mm)	2,471‡
Mean monthly water table depth (cm)	60.2 ± 2.7
Mean monthly water-filled pore space (%)	60.4 ± 2.0
Mean monthly relative humidity (%)	71.1 ± 1.47

†Humification value was classified according to Von Post (Parent and Caron 1993). Degree of decomposition is divided into 10 levels from H1 (very fibric) to H10 (very humic). ‡Rainfall value excludes the month of June 2003 because the rain gauge was stolen.

MATERIALS AND METHODS

Site description

The study was conducted in a commercial oil palm plantation (2°49′N, 111°56′E) of drained and compacted peatland in the Mukah Division of Sarawak, Malaysia. This oil palm plantation was has been established since 1997. At the commencement of this study, the oil palms were approximately 4 years old with a planting density of 160 palms ha^{-1}. Annually, 103 kg N ha^{-1} in the form of urea was applied in November 2002 and May 2003. The peat soil was classified as Typic Tropofibrist using the USDA soil classification system (Soil Survey Staff 1992). The climate at the study site was equatorial and was characterized by high even temperatures and heavy rainfall without a distinct dry season. The peat soil was very fibric with a low bulk density of 0.20 g cm^{-3} (Table 1). The other environmental characteristics of the study site are shown in Table 1.

Further information about site properties and details of measurements can be found in Melling *et al.* (2005). Climatic variables and CH_4 flux were measured at monthly intervals from August 2002 to July 2003.

Data collection and processing

CH_4 fluxes from the soil were measured using a closed chamber technique (Crill 1991). Three replicates were used in this study. At each replicate or site, an open-ended stainless steel chamber, 20 cm in diameter and 25 cm in height, was placed directly on the peat 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 installed for approximately 30 min before sampling to establish an equilibrium state (Norman *et al.* 1997). At 0, 10, 20 and 40 min intervals, 20 mL headspace samples were extracted through a silicon septum using a polypropylene syringe and placed into a 10 mL vacuum vial bottle. The samples were transported to a laboratory for analysis.

CH_4 content was determined using a Hewlett Packard 6890N (Hewlett Packard Palo Alto, CA, USA) gas chromatograph equipped with a flame ionization detector (FID) using a 2 m long Porapak N column (80/100 mesh) maintained at 50°C with a N_2 carrier gas flowing at 40 ms^{-1}. The CH_4 flux rates were calculated from the linear changes in gas concentration inside the chamber as a function of time. 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.

Soil temperature was measured at 5 and 10 cm depths at the time of sampling using a soil temperature probe. Air temperature, relative humidity and water table depth were also recorded. Monthly rainfall was also measured. Three soil samples at a depth of 0–25 cm were collected after each flux measurement at the same time as the gas samplings and bulked for both physical and chemical analyses. Chemical analyses, including NH_4^+–N and NO_3^-–N, were determined on fresh soil samples. Another three undisturbed core samples were also taken to determine bulk density and moisture content. Further details of the measurements have been described in Melling *et al.* (2005).

RESULTS

The mean annual air temperature was 30.9°C. The monthly soil temperature at depths of 5 and 10 cm was 28.0°C and 27.6°C, respectively (Table 1). The rainfall and water table patterns followed a similar seasonal variation with the highest recorded in January 2003 (Fig. 1). This showed that the seasonal change in the depth of the water table was a direct consequence of the rainfall at the experimental site.

The chemical properties of the top 25 cm of the peat soil were very acidic at pH 3.4 (Table 2). This soil also contained approximately 45% carbon and 2.0% nitrogen. On average, NO_3^-–N was higher than NH_4^+–N, indicating that the applied urea was nitrified in the peatland (Table 2). The peat soil has a very high loss of ignition of approximately 99%.

The monthly CH_4 flux is shown in Fig. 2. These were the means of the three flux measurements per month.

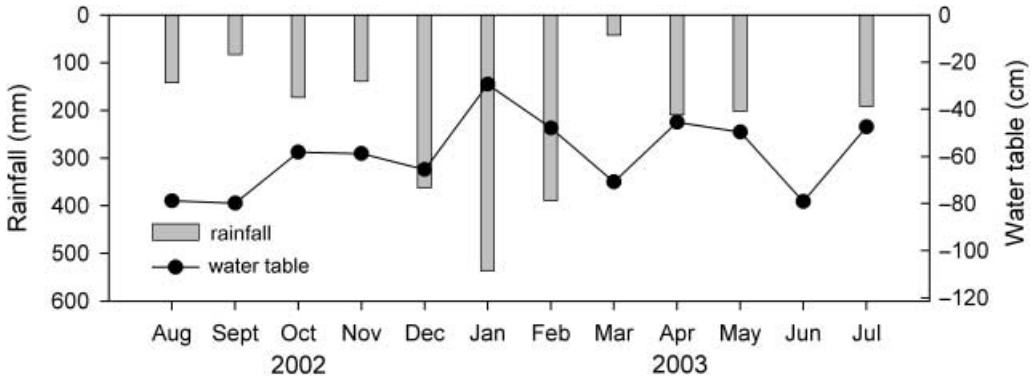

Figure 1 Monthly rainfall and water table at the oil palm plantation.

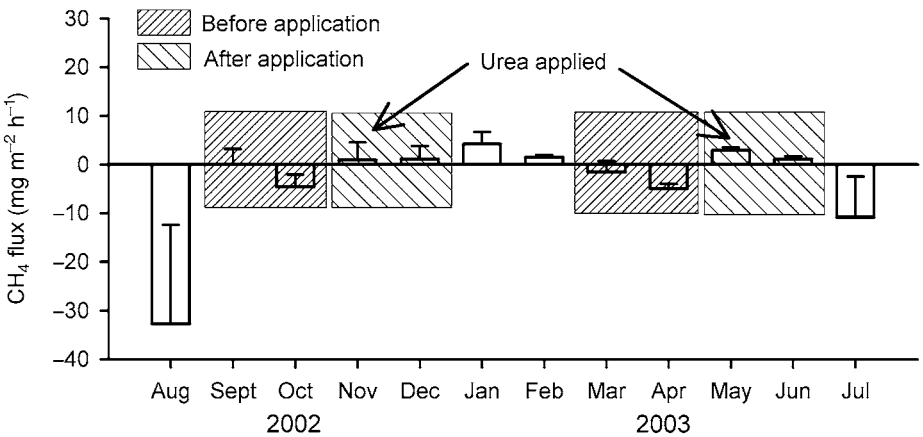

Figure 2 Monthly CH_4 flux before and after urea application at the oil palm plantation. Data represent mean ± standard error (n = 3).

Table 2 Chemical properties of the peat soil at 0–25 cm depth

Characteristics	Mean ± standar error (n = 10)
Soil pH (1:2.5)	3.4 ± 0.04
Loss of ignition (%)	99.09
Pyrophosphate solubility index (PSI)	29.97 ± 2.1
Total C (%)	44.69 ± 1.09
Total N (%)	1.96 ± 0.07
C:N ratio	23.43 ± 1.1
NH_4–N (mg kg^{-1})	58.21 ± 12.9
NO_3–N (mg kg^{-1})	198.44 ± 101.4
CEC (cmolc kg^{-1})	44.52 ± 3.1
Base saturation (%)	32.32 ± 4.5

Cation exchange capacity (CEC).

Both CH_4 emission and uptake were observed. The CH_4 fluxes ranged from −32.78 to 4.17 μg C m^{-2} h^{-1}. The highest CH_4 emission rate was recorded in January 2003. The highest CH_4 uptake rate was recorded in August 2002. The seasonal variation in CH_4 flux was not in tandem with the monthly precipitation and water table depth, which were observed to have distinct seasonal variations. The repeated measure analysis showed that there was a significant difference in the 12 months of sampling (Melling *et al.* 2005b). Annually, the oil palm ecosystem was a CH_4 sink with an uptake rate of 15 mg C m^{-2} $year^{-1}$.

DISCUSSION

Nitrogen fertilization is required for oil palm cultivation on peat to maximize growth and production. Fertilization had clearly increased the CH_4 emissions in the month of application and slightly a month later (Fig. 2).

Table 3 Comparison of methane fluxes before and after urea applications to an oil palm plantation on tropical peatland

Parameter	Methane fluxes (mg C m^{-2} h^{-1})
Before urea application	–2.754
After urea application	1.519
Difference	4.273
Standard error	0.692
P-value	0.025

The effect decreased substantially or disappeared in the third month (i.e. back to CH_4 uptake). These phenomena happened in both November 2002 and May 2003 when urea was applied. These observations were further confirmed by comparing the CH_4 fluxes 2 months before and after urea application (Table 3). The results clearly indicate that there was a significant effect of urea application on CH_4 emissions.

The inhibitory effect of urea on CH_4 oxidation has also been observed on other peatland and grasslands (Crill *et al.* 1994; Mosier *et al.* 1991). Changes in CH_4 flux were also affected by the rainfall pattern following fertilization, whereby the effect of high moisture content may have overshadowed the inhibitory effect of NH_4^+ on CH_4 oxidation. This probably explains the lower CH_4 emission in November 2002 compared with May 2003 because its water-filled pore space (WFPS) (46%) was lowest then. We also found that the negative effect of urea on CH_4 flux was short term (Fig. 3), which supports Veldkamp *et al.* (2001), who showed that the inhibition of NH_4^+ on CH_4 stopped when it was oxidized to NO_3^-, a rapid process resulting in the temporary effect.

Using a Cate–Nelson linear-plateau model (Cate and Nelson 1971), the critical soil NH_4^+ content in the top 25 cm of the peat causing CH_4 emissions in the oil palm ecosystem was 42.75 mg kg^{-1} soil (Fig. 3). The r^2 for the model was 0.90. Three points in the graph, that is, 35.9 (H), 34.9 (L) and 17.4 (L), did not fall within the model. When the soil NH_4^+ content exceeded the critical value, the CH_4 fluxes were all relatively constant and positive, indicating CH_4 emissions. We postulate that this might be because of the inhibitory effect of NH_4^+ as it nitrified to NO_3^- on CH_4 oxidation as both processes compete for soil oxygen (Hanson and Hanson 1996; Steudler *et al.* 1989; Veldkamp *et al.* 2001). Another possible explanation is that fungi and aerobic bacteria other than nitrifiers may be a stronger competitor than both methanotrophs and ammonia oxidizers, and would affect competition between the latter two. Substrate/inhibitor spectra of the key enzymes, methane monooxigenase of methanotrophs and ammonia monooxygenase of ammonia oxidizers are almost overlapping. Thus, the competitive inhibition of methane monooxygenase by ammonia (ammonium ion in solution) would have more direct effects than O_2 competition. This effect appeared to be modified by both rainfall and pyrophosphate solubility index (PSI).

When rainfall exceeded 300 mm per month (high), CH_4 emission was also high despite low soil NH_4^+ and a relatively low PSI value (Fig. 3). This effect might be attributed to a more anaerobic condition as indicated by the high WFPS and water table resulting in larger CH_4 production (Veldkamp *et al.* 2001). Low rainfall and PSI values would result in decreased CH_4 flux probably because of increased oxidation of the methane and low soluble substrate for methane production. If the

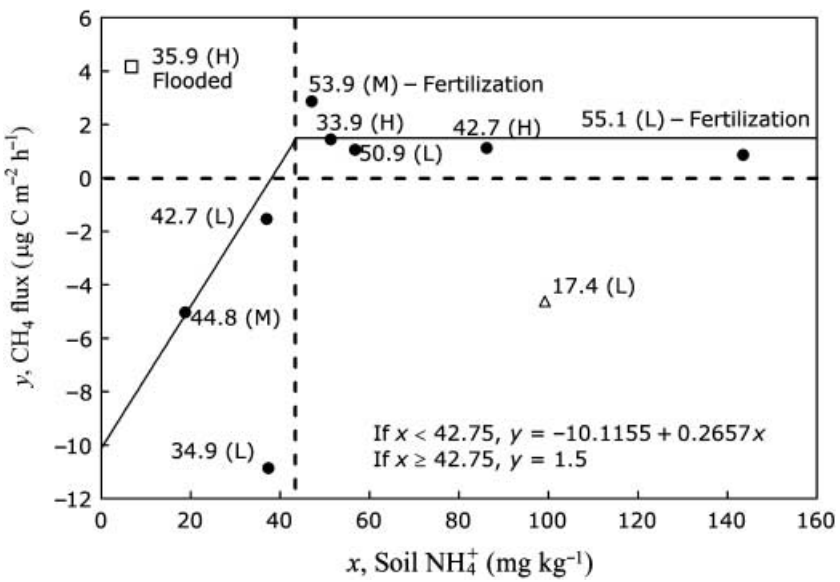

Figure 3 Interaction between soil NH_4^+, rainfall and pyrophosphate solubility index (PSI) on CH_4 flux in the oil palm ecosystem. Note: Low (L) rainfall ≤ 200 mm; moderate (M) rainfall 200–300 mm; high (H) rainfall > 300 mm. Figures in the graph show the PSI values.

fertilizer with urea was accompanied by high rainfall, CH_4 emission was enhanced because of its inhibited oxidation (Hellebrand *et al.* 2003; Steinkamp *et al.* 2001; Veldkamp *et al.* 2001). In contrast, urea application has little effect on CH_4 emission under low rainfall conditions, which decrease CH_4 production but increase ammonia volatilization (Goh and Hardter 2000). The latter would reduce the amount of NH_4–N for nitrification and, therefore, its competitive effect for soil oxygen (Veldkamp *et al.* 2001).

This study has shown that the splitting and timing of urea applications are important not only to optimize oil palm yield, but also to reduce soil NH_4^+ content to minimize CH_4 emissions and, therefore, its potential negative impact on the environment.

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