

Methane Emission from Pineapple Cultivation on a Tropical Peatland at Saratok, Malaysia

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Abstract

Information on methane emission in pineapple cultivation on peatlands is scarce. Methane emission in pineapple cultivation is important as 90% of pineapples are grown on the peat soils of Malaysia. It is essential to determine methane emission in pineapple cultivation because pineapples are Crassulacean acid metabolism plants whose effects on methane could be different from other crops grown on tropical peat soils. Methane emissions from root respiration, microbial respiration, and oxidative peat decomposition were determined in a lysimeter experiment. There were three treatments: peat soil cultivated with pineapple, bare peat soil, and bare peat soil fumigated with chloroform. Methane emissions from peat soil cultivated with pineapple, bare peat soil, and bare peat soil fumigated with chloroform were 0.65 t/ha/yr, 0.75 t/ha/yr, and 0.75 t/ha/yr, respectively. The lower methane emissions are consistent with the general believe that methane emission from cultivated peat soils is lower than those of anaerobic or water logged peat soils. Soil methane emission was affected by nitrogen fertilization under pineapple cultivation but the converse was true for soil temperature nor soil moisture.

Keywords: greenhouse gases, land degradation, lysimeter, organic soils management, peat soil

1. Introduction

Tropical peatlands cover approximately 27.1 million hectares in Southeast Asia (Hoojier et al., 2010) out of which 2.6 million hectares of these soils are located in Malaysia (Ismail & Jamaludin, 2007). Due to the increasing demand for land, peat soils have been encroached on, deforested, and drained for large-scale cultivation of crops such as oil palm (*Elaeis guineensis*), pineapple (*Ananas comosus* (L.) Merr.), and sago (*Metroxylan sagu*). At present, approximately 600, 000 hectares of the peat soil in Malaysia are cultivated with oil palm, pineapple, rubber, and sago (Ismail, 2008).

Tropical peat soils are soils formed through the accumulation of partially decayed woody plant materials under waterlogged condition. In their natural state, tropical peats emit methane (CH₄). Both disturb and undisturbed peatlands are sources of atmospheric CH₄. Methane is produced during microbial decomposition of organic matter under anaerobic condition (International Atomic Energy Agency [IAEA], 1992). Tropical peat soils are waterlogged under natural condition. This condition restricts diffusion of atmospheric oxygen into peats. This inhibits microbial decomposition of organic materials (Chimner & Cooper, 2003). Hence, microorganism are not able to metabolize organic matter into CO₂ instead, anaerobic degradation of carbon is carried out by methanogens to produce CH₄ (Parmentier, van der Molen, de Jeu, Hendriks, & Dolman, 2009).

Methane production in the anaerobic layer occurs in the form of dissolved species or as bubbles. Methane is released into the atmosphere through: molecular diffusion (peat pore spaces), ebullition (a process where bubbles in gas are formed from a dissolved state in water and channel their way to surface to the atmosphere) at the water table interface, and vascular plants with aerenchymous porous tissues which transport gases through plant roots

into the atmosphere (Dinsmore, Skiba, Billett, & Rees, 2009; Watanabe, Purwanto, Ando, Kakuda, & Jong, 2009; Farmer, Matthews, J. Smith, P. Smith, & Singh, 2011; Zhang & Jiang, 2014). Methane can also be emitted through non-microbial CH₄ production from soil organic matter under favorable conditions such as high temperature, UV radiation, and reactive oxygen species (B. Wang, Hou, Liu, & Z. Wang, 2013).

Drainage that causes water level drawdown of peat soil following land clearing for agriculture accelerates peat decomposition. Decomposition and cultivation of peats have been associated with the release of CH₄ into the atmosphere (Hadi et al., 2005; Dinsmore et al., 2009; Watanabe et al., 2009). Currently, concerns about how these anthropogenic activities in tropical peats affect the balance of greenhouse gases such as CH₄ in the atmosphere and their role in environmental degradation *vis a vis* climate change have been expressed (Couwenberg, 2011). Drained tropical peatlands emit low CH₄ through microbial processes during which CH₄ produced at the saturated layer (interface or beneath the water table) is oxidized at the unsaturated soil into CO₂ by methanotrophs (Parmentier et al., 2009; Pandey, J. Singh, D. Singh, & R. Singh, 2014). Methane emission in tropical peatlands is influenced by water table (Moore & Dalva, 1993), soil temperature (Nyakanen, Alm, Lang, Silvola, & Martikainen, 1995; Hargreaves & Fowler, 1998), and fertilization (Watanabe et al., 2009; Jassal, Black, Roy, & Ethier, 2011).

Methane emission through vascular plant mediated transport is significant (Watanabe et al., 2009). Presently, there is dearth of information on soil CH₄ emission from pineapple cultivation on drained peat soils. The contribution of pineapple cultivation on peats to greenhouse gases emission is important as 90% of pineapples are grown in the peat soils of Malaysia (Raziah & Alam, 2010). Most CH₄ emission studies on drained peats are limited to paddy, rice-soybean, and sago (Inubushi, Furukawa, Hadi, Purnomo, & Tsuruta, 2003; Hadi et al., 2005; Watanabe et al., 2009). Furthermore, most CH₄ measurements only account for total soil CH₄ emission. To date, little is known on the effects of root respiration, microbial respiration, and oxidative peat decomposition to CH₄ emission. Therefore, with the growing concern about the effects of greenhouse gases on the environmental quality and the need to achieve sustainable agriculture, it is important to determine the contribution of root respiration, microbial respiration and oxidative peat decomposition to CH₄ emission before deciding whether cultivated or degraded peats are net sinks or net sources of atmospheric greenhouse gases. Failure to account for CH₄ emission from cultivated peats could underestimate future rates of increase in the atmospheric greenhouse gases. Hence, it is important to quantify and evaluate CH₄ emissions from pineapple cultivation on tropical peat soils. Moreover, pineapple is considered a unique plant as it is classified as C3 and C4 plant or Crassulacean Acid Metabolism (CAM) plant (Mohammed Selamat, 1996) and because of this, the cultivation of this plant on peat soils could affect CH₄ emission.

The general objective of this study was to quantify CH₄ emission from a cultivated tropical peat soil. The specific objectives were to determine the: (i) emission of CH₄ from root respiration, microbial respiration, and oxidative peat decomposition and (ii) effects of soil temperature and soil moisture on soil CH₄ emission.

2. Materials and Methods

2.1 Site Description

The study was carried out at the Malaysian Agricultural Research and Development Institute (MARDI) Peat Research Station at Saratok, Sarawak, Malaysia from March 2012 to July 2013. The MARDI Peat Research Station at Saratok, Sarawak, Malaysia has a total area of 387 hectares located on a logged-over forest with a flat topography of 5 to 6 m above mean sea level. Based on the Von Post Scale of H7 to H9, the peat soil is classified as well decomposed dark brown to almost dark coloured sapric peat with a strong smell. The thickness of the peat soil ranges from 0.5 to 3.0 m. The peat soil is acidic with a mean pH ranging from 3.4 to 4.0. It has an average organic carbon content of 47%. The mean temperature of the research station ranges from 22.1 to 31.7 °C. The relative humidity of the area also ranges from 61 to 98% throughout the year. The annual mean rainfall of the peat area is 3749 mm. During the wet season (November to January), the monthly rainfall is more than 400 mm but during the dry season particularly in July, the mean rainfall is 189 mm.

2.2 Soil Chemical and Physical Analysis

Soil samples were collected at a peat excavation site (0.5 hectares) located at the research station. The experimental area was planted with Moris pineapple from 2004 to 2005, after which it was abandoned to lie fallow for six years. Soil samples were taken at depths of 0-20 cm, 20-40 cm, and 40-60 cm systematically in 12 points located over a 20 m x 12.5 m grid. The soil samples were analyzed for pH, conductivity, ammonium-N, nitrate-N, organic carbon, total nitrogen, and cation exchange capacity (CEC). Soil pH and conductivity were measured based on a 1:5 ratio soil to water suspension (Ismail, Asing, & Zulkefli, 2007). Ammonium-N and nitrate-N were determined using steam distillation (Bremner & Keeney, 1966). Soil organic carbon was

determined using the Walkley and Black method (Nelson & Sommers, 1982) whereas total nitrogen was determined using the Kjeldahl method (Bremner, 1960). Cation exchange capacity was determined using the Harada and Inoko method (Harada & Inoko, 1980). Bulk density of the peat soil was determined using the core method (Lim, 1991), and soil water holding capacity was determined using the method of Dugan, Verhoef, Robinson, and Saran (2010).

2.3 Characteristics of Lysimeters

Twelve cylindrical field lysimeters made from high density polyethylene, measuring 1.43 m in diameter and 1.58 m in height were set up in April 2012 to mimic the natural condition of drained tropical peats. The size of the lysimeters used in this study was to ensure satisfactory growth and development of pineapples for sixteen months. Twelve lysimeters were used for the three peat soil CH₄ emission treatments. The lysimeters were equipped with water spillage opening which was attached to tubes mounted on the outside of the vessel to regulate and monitor water level.

Each lysimeter was filled with peat soil up to 120 cm depth. Water loss from the soil was replenished by showering each lysimeter with 34.5 litres of rainwater. The amount of rainwater applied was based on the volume of the fabricated lysimeter and the mean annual rainfall at Saratok, Sarawak, Malaysia. The lysimeters with the peat soil were left in the open for five months to ensure that the peat soil had settled before the commencement of this study. The duration of this initial phase was based on weekly determination of the peat subsidence. The equilibrium state was achieved in September 2012 before carrying out the CH₄ measurement. Throughout the study, the water table of the peat was maintained at 50 to 60 cm from the soil surface.

2.4 Peat Soil CH₄ Emission Treatments

The treatments involved in this field lysimeter experiment were as follows: peat soil cultivated with pineapple (A), bare peat soil (B), and bare peat soil treated with chloroform (C). Each treatment had four replications. The treatments were arranged in completely randomized design.

Treatment A represents the total amount of CH₄ emitted from root respiration, microbial respiration, and peat decomposition. For this treatment, three Moris pineapple suckers were carefully planted in the lysimeters at a distance of 30 cm. The pineapples were managed by following standard agronomic practices for pineapple cultivation on peats (Mohammed Selamat & Abdul Rahman, 1996). Treatment B represents CH₄ emitted by microbial respiration and peat decomposition. Weed sprouting on the soil surface was controlled when necessary. Treatment C represents CH₄ emitted by oxidative peat decomposition. For this treatment, concentrated chloroform (64.6 litres) was applied evenly on the soil surface to eliminate microbial respiration. The amount of the chloroform used was based on the peat soil's water holding capacity. After the chloroform application, the soil was covered with cling film and canvas followed by securing it with heavy duty tape and aluminium seal lock to produce a vacuum-like condition in the lysimeters to minimize chloroform volatilization. Initial laboratory test was carried out to determine the biocidal effect of the chloroform on bacteria, fungi, and actinomycetes at one, two, three, and four weeks after chloroform application to obtain the optimum time for the chloroform application. The soil microbial population before and after the chloroform volatilization application was determined using the culture method. With this method, bacteria, fungi, and actinomycetes were enumerated as colony forming units (CFU) per gram fresh soil on nutrient agar, Rose Bengal, and actinomycetes isolation agar, respectively (Suhaimi, Emmyrafedziawati, Umi Kalsom, Sahilah, & Ismail, 2007). The chloroform was used to fumigate the peat soil one week before the soil CH₄ measurement was commenced (optimum time interval achieved for the biocidal effect on soil microorganisms).

2.5 Soil CH₄ Emission Measurements

Methane emissions from the field lysimeters were measured using the closed chamber method (IAEA, 1992). Square shape closed chambers with a hollow base and sharp edges were fabricated using acrylic material measuring 20 cm (width) x 20 cm (height) x 20 cm (length). The top of the chamber was fitted with two sampling ports plugged with rubber septum for gas sampling and thermometer installation, respectively. A battery-operated fan was also attached to the chamber to allow equilibrium gas pressure in and outside the closed chamber. The fabricated chamber was inserted vertically into the soil to a depth of 6.0 cm and care was taken to avoid disturbance to the surrounding soil. The chamber was covered with aluminium foil to minimize the effect of temperature difference within and outside the chamber.

Extracted gas samples from the chamber were analyzed for CH₄ using gas chromatography (Agilent 7890A) equipped with flame ionization detector (FID). The CH₄ results were based on the measured CH₄ from treatments A, B, and C in the wet and dry seasons. The values were averaged and converted into units of t/ha/yr.

The gas flux was calculated from the increase in the chamber concentration over time using the chamber volume and soil area covered, using the following equation (IAEA, 1992; Widen & Lindroth, 2003; Zulkefli, Lim Kim Choo, & Ismail, 2010):

$$Flux = [d(CH_4)/dt] \times PV/ART \quad (1)$$

where $d(CH_4)/dt$ is the evolution rate of CH_4 within the chamber headspace at a given time after putting the chamber into the soil, P is the atmospheric pressure, V is the volume headspace gas within the chamber, A is the area of soil enclosed by the chamber, R is the gas constant, and T is the air temperature.

The gas flux was measured in the early morning (2.40 a.m. to 5.55 a.m.), morning (7.15 a.m. to 10.30 a.m.), mid-morning to afternoon (10.35 a.m. to 1.50 p.m.), afternoon (1.55 p.m. to 5.10 p.m.), evening (8.00 p.m. to 11.15 p.m.), and night (11.20 p.m. to 2.35 a.m.). The flux measurements were carried out in September 2012, November 2012, and January 2013 to represent the concentrations of CH_4 in the wet season whereas April 2013 and July 2013 flux measurements represent the concentrations of CH_4 in the dry season. Soil temperature and moisture were measured using Eijkelkamp IP68 and ML3 sensors, respectively. Rainfall, temperature, and air humidity data were also recorded using a portable weather station (WatchDog 2900) installed at the experimental site.

2.6 Statistical Analysis

Treatment effects were tested using analysis of variance (ANOVA) whereas means of treatments were compared using Duncan's New Multiple Range Test at $p \leq 0.05$. The relationships between CH_4 emission, soil temperature, and soil moisture were analyzed using Pearson correlation analysis. The statistical software used for these statistical analyses was the Statistical Analysis System (SAS) Version 9.1.

3. Results

3.1 Peat Physical and Chemical Properties

Results of peat soil properties were compared with the previously reported ranges (Table 1) for tropical peats in Southeast Asia (Andriess, 1988) and Malaysia (Andriess, 1988; Malaysian Agricultural Research and Development Institute [MARDI], 1996; Murtedza, Padmanabhan, Mei, & Siong, 2002). The bulk density of the peat soil at 10 cm ranged from 0.09 to 0.18 g/cm^3 whereas water holding capacity of the peat soil was 40.2%. Soil moisture increased with increasing depth. Values of pH, conductivity, CEC, total organic carbon, and total nitrogen of the peat soil are within the reported range (Andriess, 1988; MARDI, 1996; Murtedza et al., 2002; STRAPEAT, Universiti Malaysia Sarawak [UNIMAS], & National Resources and Environment Boards [NREB], 2004). The soil chemical properties showed no significant difference with depth except for total nitrogen, ammonium-N, and nitrate-N. The total nitrogen of the soil was high. The total nitrogen ranged from 1.1 to 1.3%. Ammonium-N ranged from 94.8 to 138.5 mg/L whereas nitrate-N ranged from 48.8 to 72.0 mg/L at the three soil depths.

Table 1. Physical and chemical properties of a drained peat soil sampled at different depths

Variable	Mean (0 to 10 cm)	Results per soil depth (cm)			Reported range
		0 to 20 cm	20 to 40 cm	40 to 60 cm	
Physical properties					
Bulk density (g/cm^3)	0.14				0.09-0.12 (Andriess, 1988)
Water holding capacity (%)	40.2				275-322 (Andriess, 1988)
Moisture (%)		80.9 ^c	84.9 ^b	88.8 ^a	90-95 (Murtedza et al., 2002)
Chemical properties					
pH		3.8 ^a ± 0.1	3.9 ^a ± 0.1	3.9 ^a ± 0.1	3.0-4.5 (Andriess, 1988)
Conductivity ($\mu S/cm$)		178.5 ^a ± 4.6	175.4 ^a ± 4.3	172.7 ^a ± 2.4	< 200 (MARDI, 1996)
Cation exchange capacity (cmol ₍₊₎ /kg)		146.4 ^a ± 20.1	137.6 ^a ± 13.7	175.6 ^a ± 34.9	200 (Andriess, 1988)
Total organic carbon (%)		40.0 ^a ± 0.8	39.8 ^a ± 1.4	36.5 ^a ± 1.1	12-60 (Andriess, 1988) 20.4-38.4 (STRAPEAT et al., 2004)
Total nitrogen (%)		1.33 ^a ± 0.03	1.18 ^b ± 0.04	1.12 ^b ± 0.03	1.10-1.67 (Murtedza et al., 2002)
Ammonium-Nitrogen (mg/L)		138.5 ^a ± 16.2	100.0 ^b ± 4.2	94.8 ^b ± 7.7	n.a.
Nitrate-Nitrogen (mg/L)		72.0 ^a ± 5.4	48.8 ^b ± 6.3	65.8 ^{ab} ± 3.0	n.a.

Values (mean ± standard error) with different letter across the column are significantly different at $p \leq 0.05$.

n.a. = not available

3.2 Soil CH₄ Emission

Methane emissions under treatments A, B, and C varied in the wet and dry seasons (Figure 1). In the wet season, the CH₄ emission under treatment C was significantly higher than those of treatments A and B. However, in the dry season, the CH₄ emission under treatment B was higher, followed by treatment A, and treatment C.

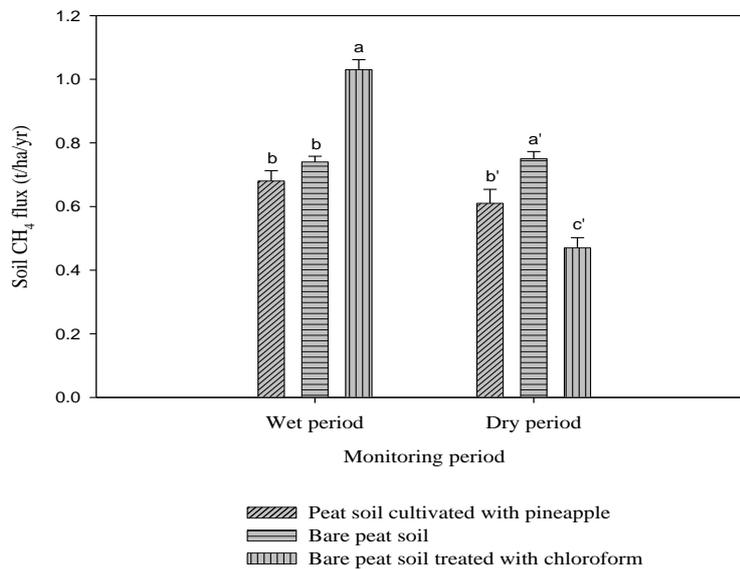


Figure 1. Soil CH₄ emission (wet and dry seasons) from peat soil cultivated with pineapple, bare peat soil, and chloroform fumigated peat soil. (Error bars represent standard error and soil mean fluxes with different letters are significantly different at $p \leq 0.05$)

The CH₄ emission showed no specific trend with time of sampling (Figure 2). The CH₄ emission was generally similar in the wet season. In the dry season, the CH₄ emission increased from early morning to mid-morning to afternoon. However, the CH₄ emissions in the afternoon, evening and night were similar during the wet and dry seasons.

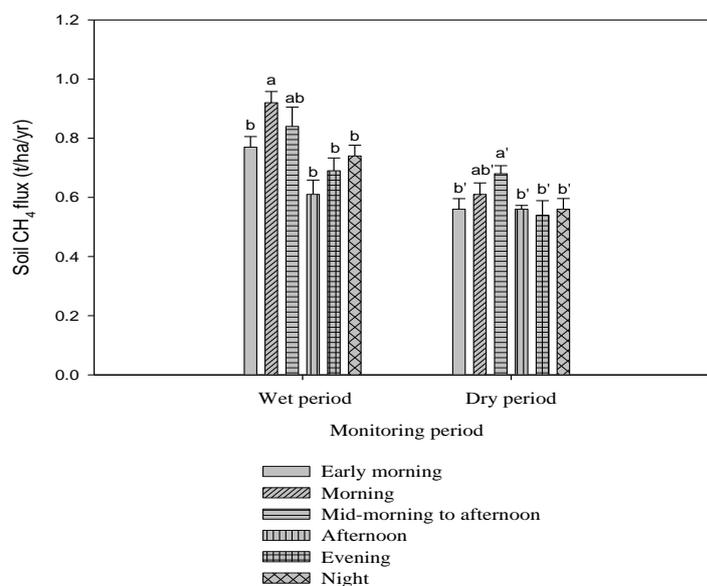


Figure 2. Soil CH₄ emission (at different times of the day and different seasons) from drained tropical peat. (Error bars represent standard error and soil mean fluxes with different letters are significantly different at $p \leq 0.05$)

4. Discussion

4.1 Peat Physical and Chemical Properties

The bulk density of the peat soil is typical of a sapric peat. The bulk density was determined at 10 cm due to the saturated condition of the excavation site. The water holding capacity was below the reported range because its determination was based on oven-dry weight method (Andriessse, 1988). The increasing moisture content with increasing peat soil depth is related to the high water table at the excavation site. However, removal of trees and debris after land clearing may have accelerated oxidative decomposition. The pH of the peat soil was low, suggesting a need for liming before being cultivated. The lower conductivity of the peat soil indicates that the soil is not saline as the research station is drained by two large tidal rivers (Sebelak River and Nyabor River). The intrusion of salt water at the station is prevented by a tidal gate constructed at the main outlet leading to Nyabor River. The CEC of the peat soil is high because of lignin-derivates formed during decomposition. Ion exchange in peats is related to carboxyl and phenolic radicals of humic substances and hemicelluloses (Andriessse, 1988). However, the CEC obtained is higher than the reported range (MARDI, 1996). This may be attributed to the past liming activities at the excavation site. This area was cultivated with pineapples from 2004 to 2005. The high organic carbon content is due to the botanical origin (woody) of the sapric peat (Andriessse, 1988; Murtedza et al., 2002). Total nitrogen, ammonium-N, and nitrate-N contents decreased with increasing soil depth (from 0-20 cm to 20-40 cm depths) because decomposition of peats generally decreases (low oxidation with increasing water content) down the soil profile (Andriessse, 1988). Furthermore, tropical peats are generally higher in lignin but lower in cellulose. Microbes decompose cellulose easily thus, leaving behind the resistant lignin as the peat decomposes thereby increasing nitrogen content.

4.2 Soil CH₄ Emission

Soil CH₄ emission under treatment A was affected by the availability of electron acceptors particularly nitrate from the fertilization (Jassal et al., 2011; Sirin & Laine, 2012). This observation is consistent with the fertilizer applications at 4.5 and 9 months old of the pineapple plants in September 2012 and January 2013, respectively (Table 2). The fertilizers applied were foliar and compound fertilizers that had urea and ammonium sulfate. These fertilizers might have increased nitrate content of the soil. Nitrate is water soluble such that leaches to the anoxic layer to inhibit CH₄ production (Jassal et al., 2011; Sirin & Laine, 2012). The shallow roots of the pineapple plants and depth of the water table in the lysimeter might have restricted CH₄ emission through vascular plant-mediated transport (Dinsmore et al., 2009).

Table 2. Fertilizer management for pineapple cultivation on a drained tropical peat soil

Months after planting	Activities	Fertilizer description	
		Type	Rate
1.5 months (05 June 2012)	First foliar fertilizer application	Mixture of copper sulfate (42 g), iron sulfate (21 g), zinc sulfate (42 g) and lime (640 g) dissolved in 18 litres of water.	50 mL per plant
3 months (19 July 2012)	First compound fertilizer application	A 100 kg of compound fertilizer is a mixture of 72 kg of ammonium sulfate, 1 kg of Christmas island rock phosphate (CIRP) and 27 kg of muriate potash (MP).	20 g per plant
4.5 months (03 September 2012)	Second foliar fertilizer application	Mixture of copper sulfate (42 g), iron sulfate (21 g), zinc sulfate (42 g), lime (640 g) and urea (640 g) dissolved in 18 litres of water.	100 mL per plant
6 months (18 October 2012)	Second compound fertilizer application	A 100 kg of compound fertilizer is a mixture of 72 kg of ammonium sulfate, 1 kg of Christmas island rock phosphate (CIRP) and 27 kg of muriate potash (MP).	20 g per plant
9 months (16 January 2013)	Third compound fertilizer application	A 100 kg of compound fertilizer is a mixture of 72 kg of ammonium sulfate, 1 kg of Christmas island rock phosphate (CIRP) and 27 kg of muriate potash (MP).	20 g per plant

The CH₄ emission under treatment B could be attributed to the methanogenic and methanotrophic microorganisms because these organisms are known to be responsible for CH₄ production and consumption (Parmentier et al., 2009). The CH₄ emission under treatment B might have been affected by the oxidation of CH₄ to CO₂ by methanotrophs (Kasimir-Klemedtsson et al., 1997; Kløve, Sveistrup, & Hauge, 2010).

The CH₄ emission under treatment C was affected by oxidative peat decomposition (shrinkage and consolidation) as the fumigant (chloroform) used inhibited microbial respiration. Bacteria and actinomycetes populations before and after fumigation were statistically similar. Fungi were not detected in this present study. These findings are in agreement with previous findings that had demonstrated that chloroform could effectively kill (94% to 99%) microorganisms (Jenkinson and Powlson, 1976; Ingham & Horton 1987; Dickens & Anderson, 1999; Toyota, Ritz, & Young, 1996; Hu & van Bruggen, 1998). The effectiveness of the fumigation is supported by the

decrease in the mean soil microbial biomass carbon (Table 3). However, it must be stressed that the lower population of soil microorganisms and reduction in soil microbial biomass carbon after chloroform fumigation does not fully suggest CH₄ emission through the inhibition of microbial respiration. The present study failed to consider microbiology bioassays to verify the contribution of microbial respiration (methanogenic and methanotrophic communities) to CH₄ emission. The insignificant difference in the peat subsidence rates recorded throughout the duration of this study regardless of treatments suggests that the chloroform used did not affect CH₄ emission due to oxidative peat decomposition. This observation corroborates that of Toyota et al. (1996) who also found no significant effect of chloroform fumigation on soil bulk density and compaction.

Table 3. Effect of fumigating drained peat soil with chloroform on soil microbial biomass carbon

Monitoring cycle	Mean soil microbial biomass carbon ($\mu\text{g C/g soil}$)
Initial before chloroform application	94.7 ^a
September 2012	29.6 ^f
November 2012	73.4 ^b
January 2013	56.0 ^d
April 2013	67.2 ^c
July 2013	46.0 ^e

Mean values with different letters are significantly different at $p \leq 0.05$.

It was also possible that the CH₄ was emitted from non-microbial production of CH₄ sources such as lignin and humic acids (Wang et al., 2013). This might have occurred under moderate temperature fluctuation of the tropics (Table 4) as peats are high in organic matter besides being natural polyelectrolyte with substances such as humic acids, fulvic acids, humin, lignin, and carbohydrate (Helal Udin, Ahmad Sujari, & Mohd. Nawi, 2003; Allen, McKay, & Porter, 2004; Zulfikar, Novita, Hertadi, & Djajanti, 2013).

Table 4. Day and night temperatures of the experimental site (Saratok, Malaysia)

Variable	Wet season			Dry season	
	September 2012	November 2012	January 2013	April 2013	July 2013
Mean day time temperature (°C)	26.7	29.2	29.6	26.3	27.0
Mean night time temperature (°C)	23.6	24.9	24.5	24.6	24.7
Mean day and night temperature differences (°C)	3.1	4.3	5.1	1.7	2.3
	Mean soil temperature (°C)				
Early morning	29.8 ^a	30.0 ^{bc}	28.2 ^{bc}	30.1 ^a	28.7 ^b
Morning	30.8 ^a	32.1 ^{ab}	29.8 ^a	30.5 ^a	29.5 ^b
Mid-morning to afternoon	30.9 ^a	32.8 ^a	30.7 ^a	30.5 ^a	30.6 ^b
Afternoon	29.7 ^a	31.1 ^{abc}	30.5 ^a	29.3 ^{ab}	32.6 ^a
Evening	29.5 ^a	30.1 ^{bc}	29.4 ^{ab}	28.7 ^{ab}	29.2 ^b
Night	29.0 ^a	29.2 ^c	27.9 ^c	27.7 ^b	28.7 ^b

Means with different letter within the same column are significantly different at $p \leq 0.05$.

Regardless of season, the CH₄ emission was not affected by time of sampling and this is not consistent with the significant positive (September 2012) and negative (January 2013 and April 2013) correlations between soil CH₄ emission and soil temperature (Table 5). However, the overall data (wet and dry seasons) showed no correlation between CH₄ emission and soil temperature (Table 5). These findings also suggest that CH₄ emission is not affected by soil temperature because of the moderate fluctuation in soil temperature (0.2 and 1.6 °C) of the tropics (Table 4). There was no correlation between CH₄ emission and soil moisture except in April 2013 (Table 5) because the water table in the lysimeters was maintained at 50 and 60 cm. This finding is further supported by the insignificant correlation of the overall data (wet and dry seasons) between CH₄ emission and soil moisture (Table 5). In a related study, Kløve et al. (2010) found that changing temperature and groundwater level had little effect on CH₄ emission from cultivated peatlands.

Table 5. Relationship between soil CH₄ emission, soil temperature, and soil moisture in dry and wet seasons

Weather season	Monitoring period	Variable	Soil temperature	Soil moisture
Wet season	September 2012	Soil CH ₄ emission	r = 0.4589	r = 0.0216
			p = 0.0013	p = 0.8866
	November 2012		r = -0.2196	r = -0.0908
			p = 0.1296	p = 0.5348
January 2013	r = -0.3921		r = 0.0618	
	p = 0.0044		p = 0.6665	
Dry season	April 2013		r = -0.4511	r = -0.3749
			p = 0.0003	p = 0.0034
	July 2013	r = -0.2780	r = -0.0769	
		p = 0.0784	p = 0.6329	
Pooling data throughout the wet and dry seasons			r = -0.3980	r = -0.0325
			p = 0.5344	p = 0.6121

Top values represent Pearson's correlation coefficient (r) while bottom values represent probability level at 0.05 (n=72 for each monitoring period, n=360 for pooling data throughout wet and dry seasons).

5. Conclusion

Peat soils drained for agriculture released 0.65 t CH₄ ha/yr under peat soil cultivated with Moris pineapple, and 0.75 t CH₄ ha/yr under bare peat soil and bare peat soil treated with chloroform, respectively. The soil CH₄ emissions were neither affected by soil temperature nor by soil moisture. Soil CH₄ emission under peat soil cultivated with pineapples seemed to be affected by nitrate-based fertilization through nitrate electron acceptors by inhibiting CH₄ production. Quantification and identification of the ratio of active methanogenic and methanotrophic communities in peat and the possibility of pineapples as plant-mediated CH₄ transport may help to further verify whether drained peats are net sources or sinks of CH₄. Further research is needed to assess non-microbial CH₄ production in peat as this soil contains high organic matter with lignin and humic acids as its major components.

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