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Water Table Fluctuation and Methane Emission in Pineapples (*Ananas comosus* (L.) Merr.) Cultivated on a Tropical Peatland

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Abstract: Inappropriate drainage and agricultural development on tropical peatland may lead to an increase in methane (CH_4) emission, thus expediting the rate of global warming and climate change. It was hypothesized that water table fluctuation affects CH_4 emission in pineapple cultivation on tropical peat soils. The objectives of this study were to: (i) quantify CH_4 emission from a tropical peat soil cultivated with pineapple and (ii) determine the effects of water table depth on CH_4 emission from a peat soil under simulated water table fluctuation. Soil CH_4 emissions from an open field pineapple cultivation system and field lysimeters were determined using the closed chamber method. High-density polyethylene field lysimeters were set up to simulate the natural condition of cultivated drained peat soils under different water table fluctuations. The soil CH_4 flux was measured at five time intervals to obtain a 24 h CH_4 emission in the dry and wet seasons during low- and high-water tables. Soil CH_4 emissions from open field pineapple cultivation were significantly lower compared with field lysimeters under simulated water table fluctuation. Soil CH_4 emissions throughout the dry and wet seasons irrespective of water table fluctuation were not affected by soil temperature but emissions were influenced by the balance between methanogenic and methanotrophic microorganisms controlling CH_4 production and consumption, CH_4 transportation through molecular diffusion via peat pore spaces, and non-microbial CH_4 production in peat soils. Findings from the study suggest that water table fluctuation at the soil–water interface relatively controls the soil CH_4 emission from lysimeters under simulated low- and high-water table fluctuation. The findings of this study provide an understanding of the effects of water table fluctuation on CH_4 emission in a tropical peatland cultivated with pineapple.

Keywords: drained peat; greenhouse gas; global warming; organic soil; pineapple; water table

1. Introduction

Drained peatlands worldwide emit approximately 2 Gt of carbon dioxide (CO_2) through microbial peat oxidation or peat fires representing 5% of all anthropogenic greenhouse gas (GHG) emissions [1]. Carbon dioxide emitted from peatlands has been implicated in the ongoing global warming debate [2]. Unlike CO_2, which is cycled and released into the atmosphere, methane (CH_4) is emitted mostly from agricultural activities [3]. Methane contributes to significant anthropogenic GHG and the concentration of CH_4 is on the increase [4,5]. The pathways of CH_4 emissions are through aerobic and anaerobic microbial respiration, root respiration, peat oxidation, nitrification, and denitrification although the determinant factors which affect CH_4 emissions are land-use type [6], peat type [7], photosynthetic activities [8], and water table fluctuation [9]. Carbon (C) is transformed and stored in different pools within the C cycle through, for example, burning of fossil fuels or decomposition of soil organic matter in the form of C gases into the atmosphere, whereas photosynthesis locks atmospheric C in plant tissues and deposition of organic-rich sediments on the ocean floor locks C in geologic rocks and sediments.

The increasing interest in reducing CH_4 emissions to meet global temperature targets is because of the short atmospheric life span of CH_4 which is approximately 10 years, but CH_4 has relatively high global warming potential [10]. Current and future regional and global CH_4 budgets and mitigation strategies require better quantitative and process-based understanding of CH_4 sources, pathways, and removals under climate and land-use change [11]. According to Leifeld [12], peatland rewetting is a cost-effective measure to curb GHG emissions, however, increasing water table depth increases CH_4 emissions [13]. Lowering peatland water tables increases peat decomposition rates because of enhanced microbial degradation of organic matter [14]. It must be stressed that the understanding of soil C flux based on studies conducted in boreal and temperate peats is not fully applicable to tropical peatland because of differences in environmental factors, peat soil properties, peat temperature, peatland-use practices, vegetation composition and structure, and microbial diversity and population.

Tropical peatlands are commonly developed for agriculture. Huang et al. [15] reported that agricultural productivity in low latitudes (tropical and semi-tropical) are likely to decline due to climate change which affects world food security and farm incomes because most developing countries, including Malaysia, are located in lower latitude regions. Falling farm incomes will increase poverty and reduce households' ability to invest for a better future [16]. According to Melling et al. [17], peat soil reclamation for agriculture involves drainage which is characterized by lowering water table and soil compaction to aerate crop root zones. Drainage of tropical peatland may cause loss of soil C reserve. Drainage via lowering of water table could change peatlands from being a C sink to a C source because drainage reverses the C flux into net CO_2 emissions [18]. The decomposition of organic materials and microbial activities releases CO_2, CH_4, organic acids, and organic particulates. The rate of C loss is related to the increased intensity of dry and wet periods. The resultant extreme water table fluctuation could affect the amount and nature of aerobic and anaerobic peat material, which subsequently affect the decomposition of peat material, microbial activity, and the crop growth. A study had revealed that the CH_4 emissions from drained tropical peatland for pineapple (*Ananas comosus* (L.) Merr.) cultivation was lower than those emitted from bare peatland and bare peatland fumigated with chloroform [19]. In this study, our approach is to estimate CH_4 emissions from tropical peatland cultivated with pineapple under fluctuating water table. Pineapple could absorb CO_2 for photosynthesis to produce carbohydrates in plant tissues. The emissions of CH_4 could be reduced through maintaining ground water level because the ground water level below the surface alters the CH_4 dynamic by weakening the potential for CH_4 production and increasing the potential for CH_4 oxidation in the upper peat layers [17,20]. Considering the potential importance of tropical peatlands in the global CH_4 budgets [21], it is essential to understand the effects of water table fluctuation on CH_4 emissions from tropical peatlands cultivated with, for example, pineapples.

There is lack of standard procedures to measure CH_4 emissions in tropical peatlands as reported by Ahmed and Liza [19]. Couwenberg [18] and Burrows et al. [22] suggested that GHG emissions should be measured on the soil surface using a closed chamber method [23,24]. Greenhouse gas monitoring which is conducted using the closed chamber method is limited in space (few cm^2) and time (few minutes). To date, there is limited information on CH_4 emissions from peatlands which are cultivated with pineapples that are relatively tolerant to peatlands' acidity. According to a study conducted by Raziah and Alam [25], the contribution of pineapples cultivated on tropical peatlands to CH_4 emissions is important because 90% of pineapples are grown on peatlands of Malaysia. In this study, it was hypothesized that peatland water table fluctuation will affect the emission of CH_4 in pineapple cultivation on tropical peatlands. This assumption is premised on the fact that peatland water table fluctuation could minimize the CH_4 emissions through suppression of the anaerobic decomposition of organic matter (reduction of CO_2 by H_2) after which it is affected by the balance of CH_4 production and oxidation. Also, regulating water table level could control the peatland water temperature because increasing soil temperature leads to an increase in CH_4 emission.

The research questions that were addressed in this study were: (i) does water table depth affect CH_4 emission from tropical peatlands cultivated with pineapples? and (ii) what is the amount of CH_4 emitted from tropical peatland which are cultivated with pineapple in relation to simulated water table fluctuation? The quantification of CH_4 emission was carried out in the dry season (July and August 2015) and wet season (September and December 2015) to take into account the effects of temperature. Warm peatlands transformed soil organic C from a C sink to a C source [26] with well-drained soils releasing CO_2 to the atmosphere [27]. However, the decomposition of organic matter and peatland temperature in relation to water table fluctuation and CH_4 emission from a tropical peatland cultivated with pineapples have scarcely been explored. Thus, this study was carried out to: (i) determine the effects of water table depth and CH_4 loss from a tropical peatland cultivated with pineapples; (ii) quantify CH_4 loss in a tropical peatland under simulated water table fluctuation; and (iii) determine the effects of water table fluctuation on soil temperature during CH_4 emission.

The implication of regulating water table level as an approach to minimizing CH_4 emission from a tropical peat soil cultivated with pineapples is an attempt to hinder CH_4 emission or consumption. It is well known that the pathways of CH_4 emission are diffusion, ebullition, and plant-mediated transport. This study focuses on the loss of CH_4 from a tropical peatland cultivated with pineapples because different vegetation growing on the same peatland results in differences in CH_4 emission or consumption. According to Hu et al. [28], under forest vegetation, soil served as a net sink of CH_4, whereas maize field (*Zea mays* L.) was essentially CH_4 neutral, and a paddy field was a net source of CH_4 diffused to the atmosphere. The findings suggested that the water table fluctuation has significant effects on CH_4 emission apart from the different crop-mediated transport. Most of the crop mediated transport are focused on the aerenchyma and not on the crassulacean acid metabolism plants such as pineapple. Aerenchyma is a type of plant that has porous root tissue, particularly well developed in wetland plants, which enables diffusive flux of gases from above-ground tissues to root tips [29]. Owing to this, most of the CH_4 emission studies on drained peatlands are limited to rice, soybean, and sago [23,30] with little exploration focus on the pineapple [19]. Our approach was not only limited to determining the effects of water table fluctuation on CH_4 emitted from a tropical peatland cultivated with pineapples, but it was also focused on the measurements of soil CH_4 emission. This study also provides information on the mechanism of CH_4 emission from different water table depth and the amount of CH_4 emission from dry and wet seasons. This study partly shows that appropriately reclaimed land use on tropical peatlands favours low CH_4 emission, and benefits pineapple planters, economy, society, and the environment.

2. Materials and Methods

2.1. Site Description for Soil Methane Emission from Field Cultivated with Pineapples

The study was carried out to quantify C losses in the form of CO_2 (data on CO_2 emissions have been published in 2017) and CH_4 in a tropical peatland subjected to water table fluctuation. The study was carried out under field conditions and simulated lysimeter at the Malaysian Agricultural Research and Development Institute (MARDI), Sesang, Saratok, Sarawak, Malaysia (Figure 1). The study area of 387 hectares (ha) was located on the logged-over forest with a flat topography of 5 to 6 m above the mean sea level. Based on the Von Post scale of H7 to H9 [31], the peatland is classified as well decomposed dark brown to dark coloured sapric peat with a strong smell and the thickness of 0.5 to 3.0 m. The average temperature of the area ranges from 22.1 to 31.7 °C while the relative humidity of the area ranges from 61% to 98% humidity with annual mean rainfall of 3749 mm. From November to January (wet season), the monthly rainfall is greater than 400 mm, whereas the mean rainfall during the dry season particularly in July is 189 mm [19]. The area of the peatland cultivated with *Moris* pineapple was 0.21 hectares (Figure 2). The Moris pineapple were planted in two rows with a planting distance of 30 cm × 60 cm × 90 cm, and the pineapples were managed according to the standard agronomic practices for pineapple management on tropical peat soils. Soil CH_4 flux measurements were carried out using the closed chamber method [32] on a 10 m × 10 m plot with five replications. The study was carried in the dry (July and August 2015) and wet (September and December 2015) seasons.

Figure 1. Location of study site in Sesang, Saratok, Sarawak, Malaysia.

Figure 2. Study site of peatland cultivated with *Ananas comosus*.

2.2. Establishment of Lysimeters for Methane Estimation under Simulated Water Table Fluctuation

Ten cylindrical field lysimeters made from high-density polyethylene (HDPE), 0.56 m in diameter and 0.97 m in height, were set up to simulate the natural condition of drained tropical peats (Figure 3). The size of the lysimeters used in this study was designed to ensure satisfactory growth and development of the pineapple. The lysimeters were equipped with a water spillage opening which was attached to clear tubes mounted on the outside of the vessel to regulate and monitor water level. Each lysimeter was filled with peat soil up to 0.90 m depth (Figure 3). Water loss from the soil was replenished by showering each lysimeter with rainwater. The amounts of the rainwater added were 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 field for five months (January to June 2015) to equilibrate. During the modification of the lysimeter, clear tubing and water spillage openings were attached to one side of the lysimeter to regulate and monitor the water level. Before the lysimeter was filled with peat soil, a polyvinyl chloride (PVC) pipe was installed vertically onto the soil to enable the bailer to reach the bottom of the lysimeter (Figure 3). The water table in the lysimeter was controlled by draining excess water through the water spillage opening or watering the peat soil with rainwater to the desired water table depth to simulate the effects of drainage and rainfall. During rainy days, the lysimeter was covered with a plastic cover to maintain a consistent water level. The depth of the water table in the lysimeter was controlled at 0 m and 0.9 m from the soil surface to represent the driest (low water table) and wettest (high water table) months, respectively.

Figure 3. Fabricated field lysimeter made from high density polyethylene.

2.3. Estimation of Soil Methane Emission during Water Table Fluctuation

Soil CH_4 emissions from the field and lysimeters were measured using the closed chamber method [32]. The CH_4 emissions from peatland were quantified using gas chromatography (Agilent 7890A) equipped with a thermal conductivity detector (TCD). The chambers were placed vertically on the soil surface between pineapple plants. The CH_4 emissions measurements were carried out on the daily basis of dry and wet months, before total draining of the plot, at 2–4 h intervals over 2–3 days duration to reflect the total of CH_4 losses through the soil surface. The size of the closed chamber was 20 cm $\times$ 20 cm $\times$ 20 cm and made up of acrylic (Figure 4). The top of the chamber was fitted with two sampling ports plugged with a rubber septum for gas sampling and thermometer installation, respectively (Figure 4). A battery-operated fan was also attached to the chamber to allow equilibrium gas pressure in and outside the closed chamber (Figure 4). The chamber was covered with a reflective aluminium foil to minimize the effect of temperature differences within and outside the chamber. The headspace samples of 20 mL were extracted from the chamber at 1, 2, 3, 4, 5 and 6 min using a polypropylene syringe equipped with a three-way stopcock. The extracted CH_4 gas was transferred to a 10 mL vacuum vial bottle by a double-ended hypodermic needle to be quantified using gas chromatography (Agilent 7890A, Agilent Technologies Inc., Wilmington, DE, USA) equipped with a flame ionization detector (FID). The values obtained were averaged and converted into units of t $ha^{-1} yr^{-1}$.

The CH_4 flux was calculated from the increase in the chamber concentration over time using the chamber volume and soil area covered, using the following equation:

$$\text{Flux} = [d(\text{CH}_4)/dt] \times PV/ART$$

where $d(\text{CH}_4)/(dt)$ 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 the soil closed by the chamber, R is the gas constant, and T is the air temperature [24,32].

The CH_4 flux was measured in the early morning I (06:00 to 06:35), afternoon (12:00 to 12:35), evening (18:00 to 18:35), midnight (00:00 to 00:35) and early morning II (06:00 a.m. to 06:35 a.m.) to obtain a 24 h of CH_4 emissions. The 24 h measurement was carried out to meet the gas flux measurement requirement based on the procedure described by Ahmed and Liza [19]. The flux measurements were carried out in July and August 2015 for the dry season and in September and December 2015 to represent the concentrations of CH_4 emitted in the wet season. Soil temperature at 6 cm depth were measured at the same time of the CH_4 flux measurement using a digital thermometer. Rainfall distribution data was collected from a portable weather station (WatchDog 2900ET, Spectrum Technologies Inc., Plainfield, IL, USA) installed at the experimental site. Although CH_4 fluxes were only monitored for two cycles for each weather season and results obtained might not be conclusive enough to confirm the findings on the effect of water table fluctuation on CH_4 emission, it must be emphasized that time allocated for soil CH_4 emission determination per sample was the limitation of this present study. This is because increasing the number of gas flux monitoring cycles are costly and time consuming. For example, a minimum retention time of 6 min is required for a gas sample analysed using gas chromatography, and the total samples for each CH_4 flux monitoring cycle were 450 per month.

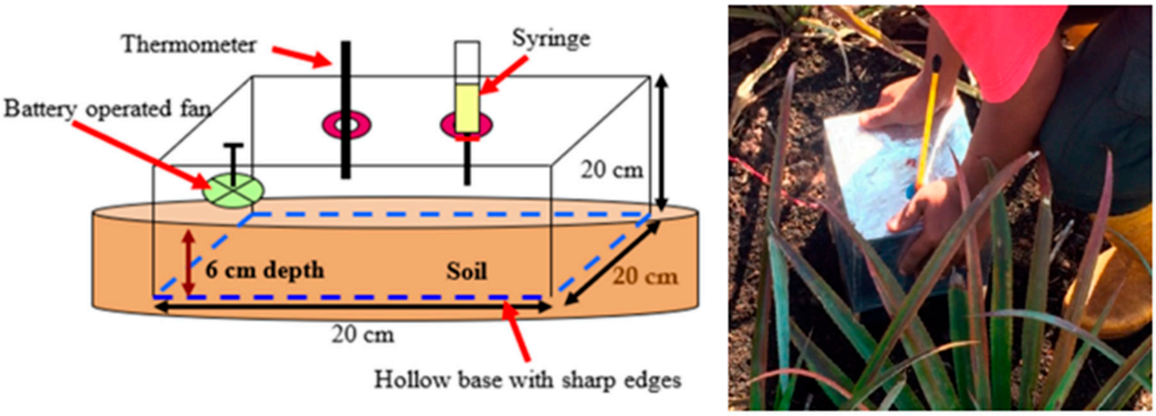


Figure 4. A closed chamber system to estimate soil methane emission from tropical peatland.

2.4. Statistical Analysis

Fluctuation of water table in relation to CH_4 emission was tested using analysis of variance (ANOVA) and means of the water table fluctuations in triplicates were compared using Duncan's new multiple range test (DNMRT) at $p \leq 0.05$. The relationships between CH_4 flux and soil temperature were analyzed using Pearson correlation analysis. The statistical software used for this analysis was the Statistical Analysis System (SAS) Version 9.3.

3. Results

3.1. Soil Methane Emissions from Peat Soils Grown with Pineapple under Open Field Cultivation System in the Dry and Wet Seasons

Soil CH_4 emissions from tropical peat soils cultivated with pineapples in the dry and wet seasons are presented in Figures 5 and 6, respectively. During the dry season (July and August 2015), the soil CH_4 emission showed no specific trend with the time of sampling but CH_4 emissions were higher at midnight (Figure 5). In July 2015, the CH_4 emissions was generally similar, whereas soil CH_4 emissions were lower in the early morning I, afternoon, evening, and early morning II than at midnight in August 2015. Compared with the wet season, soil CH_4 emissions were lower in the afternoon and at midnight during the gas flux monitoring in September and December 2015, respectively (Figure 6).

Averaged soil CH_4 emissions over 24 h from a drained peat soil cultivated with pineapples throughout the dry (July and August 2015) and wet (September and December 2015) seasons are presented in Figure 7. Soil CH_4 emissions were higher in September 2015 but emissions were lower in July, August and December 2015. However, soil CH_4 emissions in July, August and December 2015 were similar.

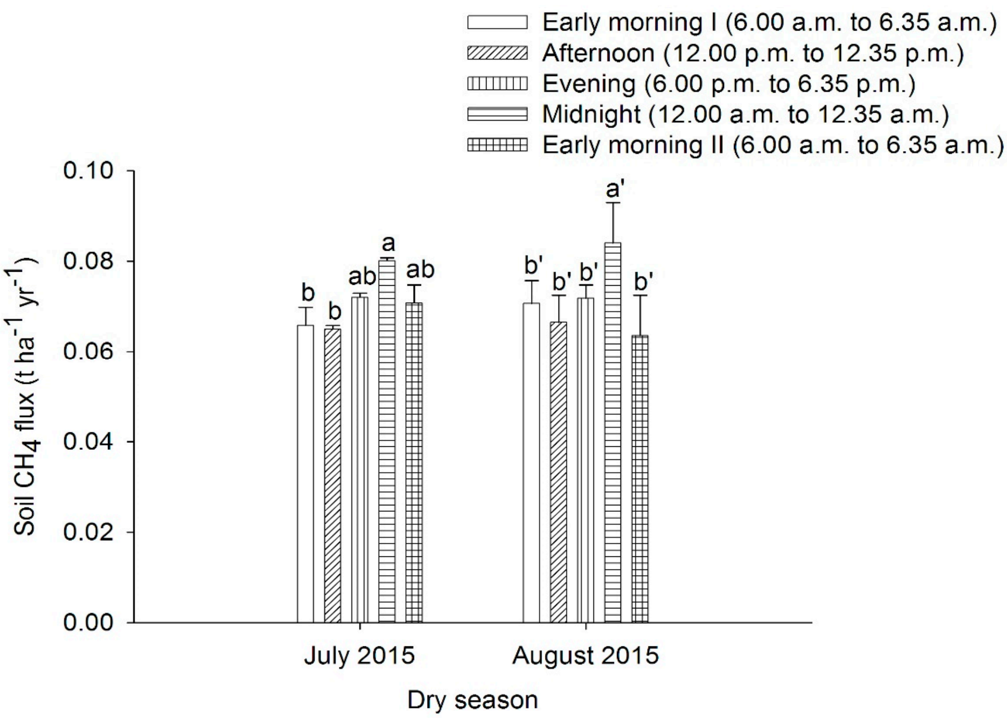


Figure 5. Soil CH_4 emissions (at different times of the day) from a tropical peatland cultivated with pineapples in the dry season (July and August 2015). Error bars represent standard error and soil mean fluxes with different letters and noted by prime are significantly different using Duncan's new multiple range test (DNMRT) at $p \leq 0.05$.

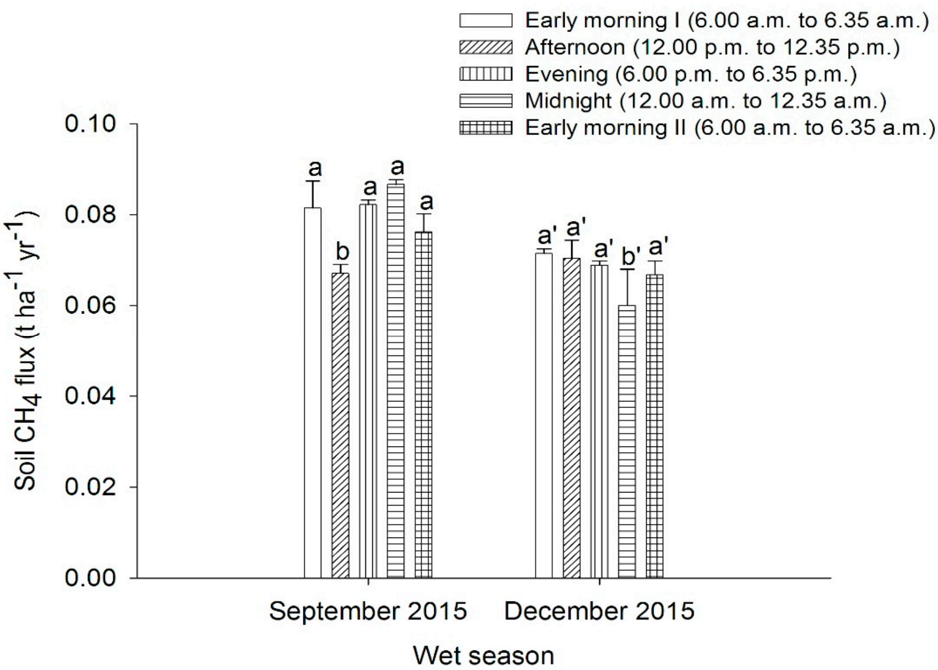


Figure 6. Soil CH_4 emissions (at different times of the day) from a tropical peatland cultivated with pineapples in the wet season (September and December 2015). Error bars represent standard error and soil mean fluxes with different letters and noted by prime are significantly different using DNMRT at $p \leq 0.05$.

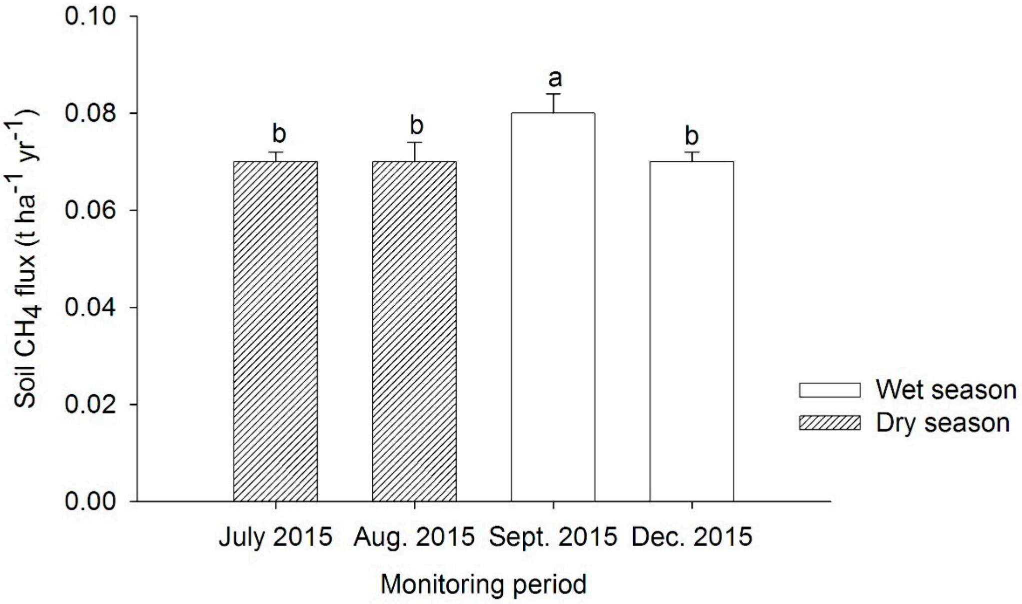


Figure 7. Averaged soil CH_4 emissions over 24 h from a tropical peat soils cultivated with pineapple throughout the dry (July and August 2015) and wet (September and December 2015) seasons. Error bars represent standard error and soil mean fluxes with different letters are significantly different using DNMRT at $p \leq 0.05$.

Throughout the CH_4 flux monitoring, soil temperature was statistically similar during the dry and wet seasons irrespective of sampling time (Table 1). Also, there was no significant correlation between CH_4 emission and soil temperature (Table 1).

Table 1. Relationship between soil CH_4 emission and soil temperature from a peat soil cultivated with pineapples throughout the dry and wet seasons in 2015.

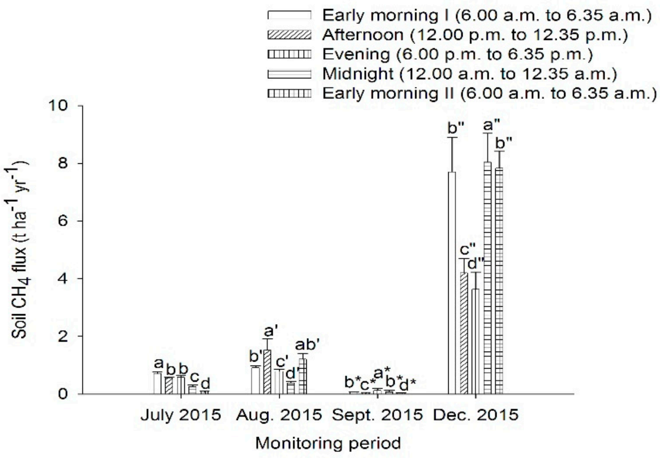
Variable	Soil Temperature (°C)			
	Dry Season Wet Season			
	July 2015	August 2015	September 2015	December 2015
Early morning I (6:00 a.m. to 6:35 a.m.)	30.7 [a]	28.3 [a]	29.0 [a]	31.0 [a]
Afternoon (12:00 p.m. to 12:35 p.m.)	25.3 [a]	27.0 [a]	25.7 [a]	25.0 [a]
Evening (6:00 p.m. to 6:35 p.m.)	28.3 [a]	29.3 [a]	29.3 [a]	29.3 [a]
Midnight (12:00 a.m. to 12:35 a.m.)	25.3 [a]	28.3 [a]	28.3 [a]	27.0 [a]
Early morning II (6:00 a.m. to 6:35 a.m.)	26.7 [a]	28.5 [a]	28.5 [a]	26.7 [a]
Soil CH_4 emission	r = −0.1191 p = 0.6725	r = 0.2209 p = 0.4286	r = −0.1386 p = 0.6224	r = −0.0529 p = 0.8513

Mean values with same letters within the same column are not significantly difference between means using DNMRT at $p \leq 0.05$. Top value indicates Pearson's correlation coefficient (r), whereas the bottom values indicate probability level at 0.05 (n = 600).

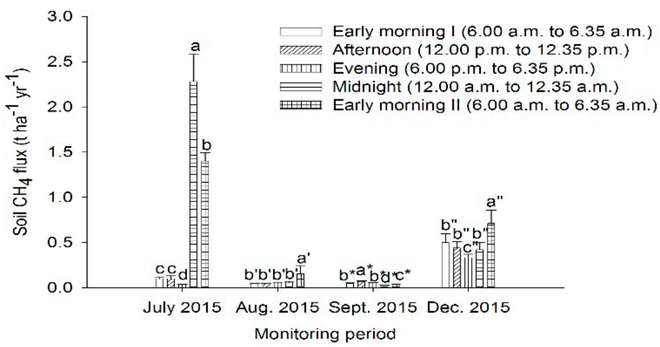
3.2. Soil Methane Emissions from Peat Soils Cultivated with Pineapples in Lysimeters under Simulated Water Table Fluctuation in the Dry and Wet Seasons

Soil CH_4 emission varied with time of sampling throughout the wet and dry seasons under low and high water table fluctuations (Figure 8a,b). At low water table during the dry season (Figure 8a), soil CH_4 emissions decreased from early morning I to early morning II in July 2015, whereas CH_4 emissions were higher in the afternoon but lower at midnight in August 2015. However, at low water table during the wet season (Figure 8a), soil CH_4 emissions were higher in the evening but lower in the early morning II in September 2015, whereas in December 2015, CH_4 emission decreased from early morning I to evening, followed by an increase at midnight, after which the CH_4 emission decreased until early morning II. Compared with lysimeters subjected to a high water table (Figure 8b), soil CH_4 emissions in the dry season were higher at midnight and early morning II in July and

August, respectively. However, at high water table during the wet season (Figure 8b), soil CH_4 emission was higher at noon in September 2015, whereas CH_4 emissions decreased from early morning I to evening, after which the CH_4 emission increased until early morning II.



(**a**)



(**b**)

Figure 8. Soil CH_4 emissions (at different times of the day) from a peat soil grown with pineapples in lysimeters under simulated water table fluctuation (**a**) low water table and (**b**) high water table throughout the dry (July and August 2015) and wet (September and December 2015) seasons. Error bars represent standard error and soil mean fluxes with different letters and noted by prime, asterisk, and double prime are significantly different using DNMRT at $p \leq 0.05$.

Averaged soil CH_4 emissions over 24 h under different water table depth varied in the dry and wet seasons (Figure 9). At low water table (0.9 m from the soil surface), averaged soil CH_4 emissions were higher in the wet season (December 2015) but lower throughout the monitoring period in July, August and September 2015. Conversely, at high water table (0 m from the soil surface), averaged soil CH_4 emissions were higher in the dry season (July 2015) but emissions were lower in August and September 2015. However, throughout the dry and wet seasons, averaged soil CH_4 emissions were significantly higher under the low water table compared with that of the high water table (Figure 10).

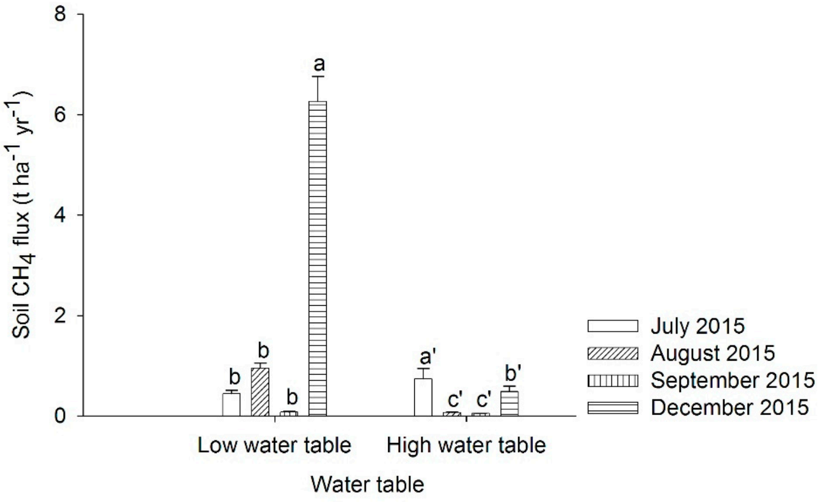


Figure 9. Averaged soil CH_4 emissions over 24 h from a peat soil cultivated with pineapples in lysimeters under low and high water tables throughout the dry (July and August 2015) and wet (September and December 2015) seasons. Error bars represent standard error and soil mean fluxes with different letters and noted by prime are significantly different using DNMRT at $p \leq 0.05$.

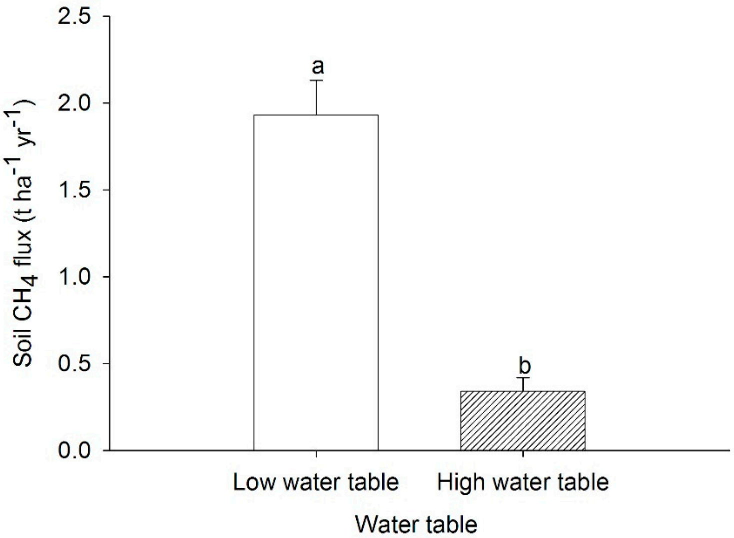


Figure 10. Averaged soil CH_4 emissions over 24 h from a peat soil grown with pineapple in lysimeters under low and high water table. Error bars represent standard error and soil mean fluxes with different letters are significantly different using DNMRT at $p \leq 0.05$.

Throughout the dry and wet seasons, soil temperature was statistically similar irrespective of water table and sampling time (Table 2). Moreover, there was no significant correlation between soil temperature and CH_4 emission (Table 2). This observation is consistent with the results obtained from the soil CH_4 measurement from open field pineapple cultivation (Table 1).

Compared with the peat soils grown with pineapple under open field cultivation system, averaged soil CH_4 emissions from pineapples in lysimeters subjected to water table fluctuation were significantly higher throughout the dry and wet seasons in 2015 (Figure 11).

Table 2. Relationship between soil CH_4 emission and soil temperature from lysimeters cultivated with pineapples under simulated water table fluctuation throughout the dry and wet seasons in 2015.

Variable	Soil Temperature (°C)							
	Dry Season				Wet Season			
	July 2015		August 2015		September 2015		December 2015	
	Low Water Table	High Water Table	Low Water Table	High Water Table	Low Water Table	High Water Table	Low Water Table	High Water Table
Early morning I (6:00 a.m. to 6:35 a.m.)	32.7 ^{a}	32.3 ^{a,b}	27.5 ^{a,b}	28.3 ^{a}	28.3 ^{a}	27.7 ^{a}	29.2 ^{a}	30.3 ^{a}
Afternoon (12:00 p.m. to 12:35 p.m.)	24.3 ^{a}	25.0 ^{a}	27.2 ^{b}	29.0 ^{a}	29.0 ^{a}	28.7 ^{a}	27.8 ^{a}	28.0 ^{a}
Evening (6:00 p.m. to 6:35 p.m.)	32.7 ^{a}	36.0 ^{a}	29.3 ^{a,b}	29.3 ^{a}	28.3 ^{a}	30.0 ^{a}	26.3 ^{a}	30.7 ^{a}
Midnight (12:00 a.m. to 12:35 a.m.)	28.0 ^{a}	24.7 ^{b}	28.3 ^{a,b}	28.2 ^{a}	29.3 ^{a}	28.7 ^{a}	29.7 ^{a}	28.7 ^{a}
Early morning II (6:00 a.m. to 6:35 a.m.)	32.0 ^{a}	28.3 ^{a,b}	29.7 ^{a}	27.7 ^{a}	28.2 ^{a}	28.0 ^{a}	27.0 ^{a}	30.0 ^{a}
Soil CH_4 emission	r = 0.2904 p = 0.2938	r = −0.0609 p = 0.8292	r = 0.4051 p = 0.1342	r = −0.0299 p = 0.9156	r = −0.0183 p = 0.9484	r = −0.0014 p = 0.9959	r = −0.1583 p = 0.5731	r = −0.4843 p = 0.0674

Mean values with same letters within the same column are not significantly difference between means using DNMRT at $p \leq 0.05$. Top value indicates Pearson's correlation coefficient (r), whereas the bottom values indicate probability level at 0.05 (n = 1200).

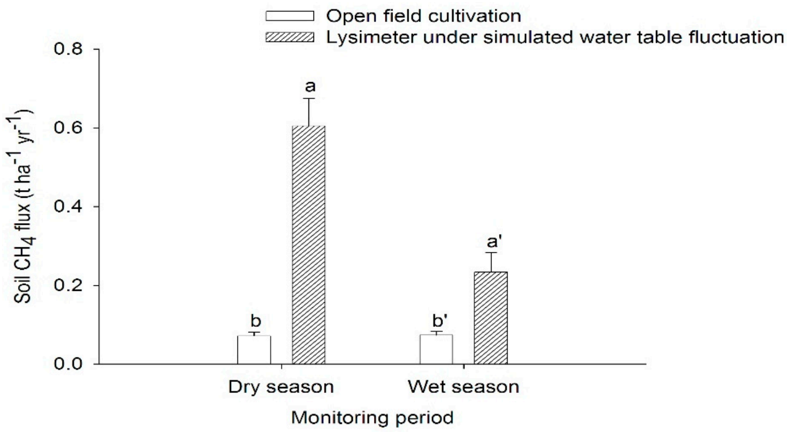


Figure 11. Averaged soil CH_4 emissions from peat soils grown with pineapples under open field cultivation system and lysimeters subjected to water table fluctuation in the dry and wet seasons. Error bars represent standard error and soil mean fluxes with different letters and noted by prime are significantly different using DNMRT at $p \leq 0.05$.

4. Discussion

4.1. Soil Methane Emissions from Peat Soils Grown with Pineapple under Open Field Cultivation System in the Dry and Wet Seasons

Differences in soil CH_4 emission across time (early morning, afternoon, evening and midnight) from pineapple cultivated peat soils could be attributed to the microbial structure in the peat soil that controls the balance between CH_4 production and CO_2 conversion and vice versa by methanogenic bacteria and methanotrophs under anaerobic and aerobic conditions [33], respectively, throughout the dry and wet seasons. Peat soils become net source of CH_4 when CH_4 production by methanogenic bacteria surpasses consumption by methanotrophic bacteria [34]. Moreover, soil CH_4 fluxes are regulated by oxygen supply and availability of labile carbon, where methanogenesis is predominant under anaerobic conditions. Also, soil CH_4 emissions might have been affected by the transportation of CH_4 by molecular diffusion through the aerobic layer of the peat soils, and through ebullition in the form of bubbles at the peat water table interface [35–37].

Although the averaged soil CH_4 emissions were not affected by the flux monitoring period throughout the dry (July and August 2015) and wet (December 2015) seasons, the higher CH_4 emission particularly in September 2015 during the wet season was because of the higher rainfall received at the experimental site amounting to 72 mm compared with the lower rainfall received in July (29 mm), August (52 mm) and September (69 mm) 2015 [38].

This result suggests that higher CH_4 is emitted under anaerobic and waterlogged conditions. The waterlogged condition of the peat soil in September 2015 might have favoured the thriving of methanogenesis bacteria under anoxic conditions, thus causing higher soil CH_4 emission. This result also corroborates previous work by Furukawa et al. [20] and Inubushi et al. [30], who reported that the increase in soil CH_4 emission is due to high rainfall.

Although soil CH_4 emission was affected by the time of sampling, the insignificant correlation between soil CH_4 emission and soil temperature regardless of seasons (dry and wet period) suggest that CH_4 emission was not affected by soil temperature due to the moderate soil temperature fluctuation during CH_4 flux measurement. The peat soil temperature ranged between 25 to 31 °C during the CH_4 sampling (Table 1).

4.2. Soil Methane Emissions from Peat Soils Cultivated with Pineapples in Lysimeters under Simulated Water Table Fluctuation in the Dry and Wet Seasons

Similar to the pineapple cultivated under an open field system, differences in soil CH_4 emission across time from field lysimeters subjected to water table fluctuation (low and high water table) relates to the microbial structure in the peat soils, particularly the methanogenic and methanotrophic microorganisms because these organisms control CH_4 production and consumption. Also, soil CH_4 release might have been influenced by the collapse of peat pores (during the soil excavation and setting up of the lysimeters) that affected CH_4 transportation through molecular diffusion, and subsequent soil subsidence in the lysimeters due to water table fluctuation.

In this present study, there was a discrepancy on the averaged soil CH_4 emissions from lysimeters under low and high water tables in the dry and wet seasons (Figure 9). The findings reported higher soil CH_4 emissions both under low and high water table in the wet (December 2015) and dry (July 2015) seasons, respectively. Moreover, averaged soil CH_4 emission under a low water table were higher compared with that of high water table. These observations were not in agreement with the general belief that soil CH_4 emission increases with a higher water table. There are no specific reasons that explain the anomaly from the findings obtained. However, the inconsistency of soil CH_4 emissions from peat the soils suggest that the factor controlling CH_4 emission from the lysimeters could be attributed to the fluctuation of the water table at the soil–water interface. The water table level and its fluctuation at the soil–water interface may have altered the intensity and duration of CH_4 production and oxidation processes throughout the dry and wet seasons.

The results on the insignificant correlation between soil temperature and CH_4 emission from lysimeters under simulated water table fluctuation irrespective of seasons was consistent with that reported for CH_4 measurement under an open field pineapple cultivation system. These observations are further supported by the fact that CH_4 emission was not affected by soil temperature because of the moderate soil temperature fluctuation (24.7 to 32.7 °C) during CH_4 flux measurement. This finding was in agreement with the study by [39,40] who reported that temperature changes had minimal effects on CH_4 emission from cultivated peatlands.

It is also possible that soil CH_4 from lysimeters and under open field pineapple cultivation was released from non-microbial production of CH_4 sources particularly humic acids and lignin [41]. The emission of non-microbial CH_4 may have occurred under moderate temperature fluctuations of the tropics because of the high amount of organic matter, humic acids, fulvic acids, lignin, humin and carbohydrate in peat soils [42–44]. In this study, the lower soil CH_4 emission from peat soils grown with pineapple under an open field cultivation system compared with that of CH_4 emission from the lysimeters throughout the dry and wet seasons (Figure 11) could be attributed to pineapple fertilization. Compound NPK fertilizers containing ammonium were applied to pineapple at 3, 6 and 9 months after planting in June, September and December 2015, respectively. The compound fertilizers might have increased nitrate content in the peat soils because nitrification increases with peat oxidation. The lower CH_4 emission due to pineapple fertilization relates to the availability of electron acceptors namely nitrate which inhibits CH_4 production [45].

Nitrate is water soluble and leaches to the water table interface leading to decreased CH_4 production in anaerobic condition. Also, water table fluctuation (50 to 70 cm from the soil surface) and lateral water movement in the peat soil (open field cultivation system) might have affected the balance between CH_4 production and consumption by methanogenic bacteria and methanotrophs. Water table depth affects the soil CH_4 emissions because it determines the depth of the oxic or anoxic boundary and redox level within the soil. By contrast, water table fluctuation at the soil–water interface, transportation of CH_4 through molecular diffusion through the aerobic peat layer and ebullition at the peat water table interface relatively explains the higher CH_4 emission from lysimeters under simulated water table fluctuation.

5. Conclusions

Soil CH_4 emission throughout the dry and wet seasons under open field pineapple cultivation and from lysimeters subjected to water table fluctuation were not affected by soil temperature but emissions were influenced by the balance between methanogenic and methanotrophic microorganisms controlling CH_4 production and consumption, CH_4 transportation via molecular diffusion through peat pore spaces, and non-microbial CH_4 production sources in peat soils namely humic acids and lignin. Although it is generally believed that a high water table increases soil CH_4 emission, findings from the study suggest that water table fluctuation at the soil-water interface relatively controls the soil CH_4 emission from lysimeters under simulated low and high water table fluctuations. The outcome of this present study demonstrated that soil CH_4 emission throughout the dry and wet seasons under an open field cultivation system was affected by the availability of nitrate electron acceptors from pineapple fertilization, which restrict CH_4 production, thus leading to lower soil CH_4 emission compared with that of CH_4 emissions from lysimeters. However, the limited number of CH_4 flux monitoring throughout the dry and wet seasons (July, August, September and December 2015) may not be conclusive enough to confirm the findings from the study. Thus, a long-term CH_4 flux monitoring period is required to confirm the findings obtained because rainfall distribution, microbial population, chamber humidity and headspace temperature may influence CH_4 emission and the outcome of the study. The findings of this study provide an understanding on the effects of water table fluctuation on CH_4 emissions in a tropical peatland under pineapple cultivation.

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