Environment, Development and Sustainability
https://doi.org/10.1007/s10668-020-01132-y

Effect of compaction on soil CO_2 and CH_4 fluxes from tropical peatland in Sarawak, Malaysia

Nur Azima Busman[1,2] · Nagamitsu Maie[3] · Che Fauziah Ishak[1] · Muhammad Firdaus Sulaiman[1] · Lulie Melling[2]

Received: 29 September 2019 / Accepted: 28 November 2020
© The Author(s), under exclusive licence to Springer Nature B.V. part of Springer Nature 2021

Abstract

Tropical peatland stores a large amount of carbon (C) and is an important C sink. In Malaysia, about 25% of the peatland area has been converted to oil palm plantation where drainage, compaction and groundwater table control are prerequisite. To date, relationship between land compaction and C emission from tropical peatland is scarcely studied. To understand the effect of compaction on soil carbon dioxide (CO_2) and methane (CH_4) flux from tropical peatland, a laboratory soil column incubation was conducted. Peat soil collected from a Mixed Peat Swamp forest were packed in polyvinyl chloride pipes to three different soil bulk densities (BD); 0.14 g cm^{-3}, 0.18 g cm^{-3} and 0.22 g cm^{-3}. Soil CO_2 and CH_4 flux from the soil columns were measured on weekly basis for twelve weeks. Total soil porosity and moisture retention of each soil BD were also determined using another set of peat sample packed into 100 cm^3 soil core ring. Soil porosity decreased while soil moisture retention increased proportionally with increasing soil BD. Soil CH_4 flux were reduced approximately by 22% with compaction. On contrary, soil CO_2 fluxes were greater ($P \leq 0.05$) at compacted soil when infiltration and percolation of rainwater become slower with time, until soil moisture becomes limiting factor. This study suggested that compaction affects water movement and gaseous transport in the peat profile, thus influences C emission from peat soil.

✉ Nur Azima Busman
zima_b67@yahoo.com

Nagamitsu Maie
maie@vmas.kitasato-u.ac.jp

Che Fauziah Ishak
cfauziah@upm.edu.my

Muhammad Firdaus Sulaiman
muhdfirdaus@upm.edu.my

Lulie Melling
luliemelling@gmail.com

[1] Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia (UPM), 43400 Serdang, Selangor, Malaysia

[2] Sarawak Tropical Peat Research Institute, Lot 6035, Kota Samarahan Expressway, 94300 Kota Samarahan, Sarawak, Malaysia

[3] School of Veterinary Medicine, Kitasato University, Towada, Aomori 034-8628, Japan

Published online: 24 January 2021

Keywords CO_2 flux · CH_4 flux · Soil compaction · Soil bulk density · Tropical peatlands

1 Introduction

Globally, peatlands cover an estimated area of 400 Mha which is equivalent to 3% of the world's land surface and stores approximately 528 Pg of C (Hodgkins et al. 2018). One-third of the C stored in peatlands (191 Pg) are located in the tropical regions covering 10–12% (30–45 Mha) of the global peatlands areas (Murdiyarso et al. 2010). In tropical region, 56% of peatlands are found in Southeast Asia, particularly in Indonesia and Malaysia, storing 68.5 Gt C (Page et al. 2011).

Over the past two decades, *ca*. 25% of peatlands area in Malaysia has been converted for industrial agriculture development, most notably for oil palm plantation (Padfield et al. 2015). Oil palm cultivation on tropical peatlands generally requires drainage of presently saturated peat by lowering the ground water level typically to a depth of 50–70 cm to improve the oil palm growth. Lowering the water level, however, induces aeration, which is favorable for microbial activity that promotes soil organic matter decomposition resulting in the C losses from peat soil (Andersen et al. 2010).

Following drainage, peatlands are mechanically compacted using heavy machinery. During mechanical compaction, soil particles are consolidated which results in decreased porosity and increased soil bulk density. Additionally, mechanical compaction reduces soil aeration, water infiltration rate and hydraulic conductivity of the soil (Nawaz et al. 2013). From agriculture point of view (Soane and Ouwerkerk 1994), mechanical compaction is generally regarded as problematic due to the effects on crop growths. However, for agricultural activity on organic soil such as peat, it has been recognized that mechanical compaction improves crops growth (Othman et al. 2009; Reichert et al. 2009; Melling et al. 2016).

Increase in bulk density of peat soil provides better anchorage of oil palm tree, reduces the rate of fertilizer leaching, increases the nutrient supply and thus optimizes the plant growth and crop yield. It was also postulated that the increase in water retention capacity will counteract the changes in water and oxygen (O_2) contents initially induced by peat drainage (Rothwell et al. 1996). Greater water retention ensures higher soil moisture content maintained above the groundwater table. High soil moisture content reduced the gases diffusion (i.e., O_2 and C O_2), creating anoxic conditions that hinders microbial activity and the rate of SOM decomposition (Beare et al. 2009). Therefore, mechanical compaction is hypothesized to influence the dynamic of C emission from drained peatland through soil moisture content and gas diffusivity.

A few studies on the effect of mechanical compaction toward peat soils for engineering purposes is available (Deboucha et al. 2008; Kolay et al. 2010) but there is scarce information on the effect of mechanical compaction on peat soils used for agriculture. In addition, most of the literature on soil compaction is based on the work conducted on mineral soil. Therefore, there is a great need to endorse the knowledge and understanding on the effect of mechanical compaction on peatlands toward C emission particularly in tropical region due to the larger agriculture development in this area.

The objective of this study is to determine the effect of soil compaction on C emission in the form of CO_2 and CH_4 fluxes from tropical peatland. For this purpose, peat soil samples were packed in the soil column into three soil bulk densities: 0.14 g cm^{-3}, 0.18 g cm^{-3} and 0.22 g cm^{-3}. Soil bulk density of 0.14 g cm^{-3} represents the bulk density of uncompacted peat soil (Firdaus et al. 2011). Soil bulk density of 0.18 g cm^{-3} and 0.22 g cm^{-3} is the representative of compacted soil, typically within the range of soil bulk densities in an oil palm plantation that have undergone mechanical compaction (Othman et al. 2009; Könönen et al. 2015; Nusantara et al. 2018). Variation in soil physical properties such as total porosity and water retention capacity from each soil bulk densities was also determined using another set of peat sample packed into 100 cm^3 soil core sampler.

2 Materials and methods

2.1 Site description

Peat soil samples were collected in the Maludam National Park, Betong Division, Sarawak (Fig. 1). Maludam National Park is occupied with 43,147 ha of tropical peatland forests (Sarawak Forestry Corporation 2013), and it has been conserved as a national park since 2000 (Monda et al. 2018). The peat swamp forest of Sarawak has six phasic communities: Mixed Peat Swamp (MPS), Alan Batu, Alan Bunga, Padang Alan, Padang Selunsur and Padang Keruntum (Anderson 1964). Each phasic community has distinct characteristic species and structures due to the topo-hydrology of the peatlands and the fertility of the peat soils (Melling 2016). MPS forest is the major forest types across a peat basin in Sarawak with wide varieties of vegetation, dominated by *Gonstylus bancanus*, *Dactylocladus stenostachys*, *Copaifera palustris* and four species of *Shorea* (Table 1; Melling et al. 2008; Mohd-Azlan and Das 2016). MPS soils were reported to age between 1600 and 5000 years before present (Sangok et al. 2020) and estimated annual decomposition rate was 0.033 y^{-1} (Sangok et al. 2017).

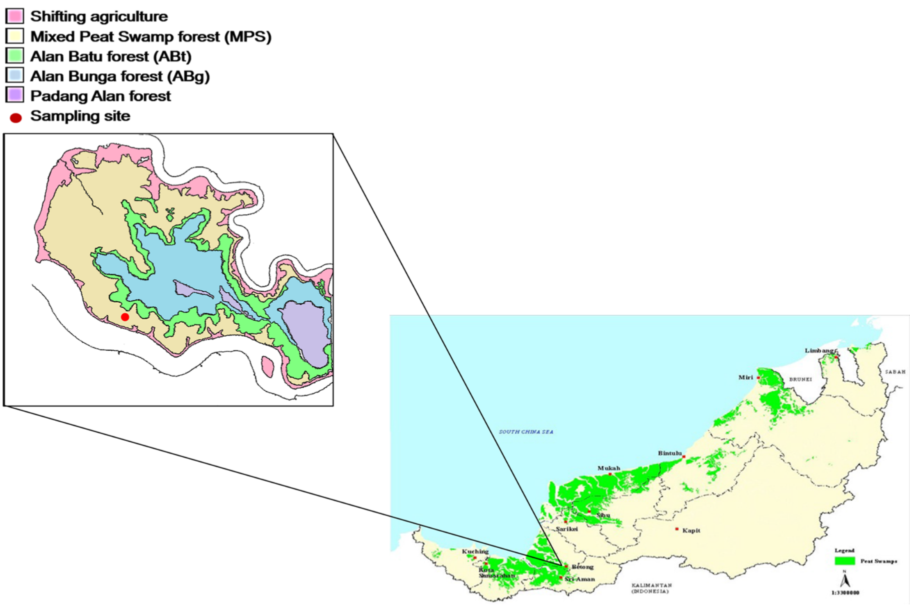

Fig. 1 Map of Sarawak, Malaysia, and location of soil sampling sites in the Maludam National Park (Melling 2016)

Table 1 General information of the sampling area in Maludam National Park

Properties	Description
GPS point	N 1° 25′ 56" E 111° 07′ 46"
Peat depth	450 cm
Vegetation	Gonystylus bancanus, Dactylocladus stenostachys, Copaifera palustris and four species of Shorea
Mean groundwater table* Min Max	− 44.8 cm 4.6 cm
Mean soil temperature*	25.5 °C
Annual mean rainfall*	2756 mm

*Data were recorded from year 2011 to 2016

2.2 Soil sampling

Two sampling points were randomly selected, each being 250 m away from the groundwater table monitoring station which were installed in the MPS forest. At each sampling point, a soil pit of 100 cm depth was dug, and samples in blocks were collected from the pit wall between 50 and 70 cm layer using a chainsaw. Samples at 50–70 cm depth were selected due to the monthly groundwater table fluctuation in MPS forest, representing soil layer that rarely undergone aerobic conditions for a long period. Approximately 100 kg of soil samples were collected from each sampling point, with a total of 200 kg soil samples. The collected sample were thoroughly mixed, with visible roots and branches being removed by hands to make composite samples and brought back to Sarawak Tropical Peat Research Institute for further laboratory analysis. In the laboratory, soil samples were air-dried until 75% moisture content. A portion of the air-dried samples were used for chemical properties analysis while the remaining were used for laboratory soil column incubation experiment.

2.3 Chemical analysis of peat soil

Soil pH (H_2O) was measured at the soil to water ratio of 2:5 (w/v) with a pH meter probe (Metrohm 827, Metrohm, Herisau, Switzerland), and ash content was determined using a thermogravimetric analyzer (TGA 701, Leco, St. Joseph, MI, USA). Total C and total nitrogen (N) contents were determined using a CN analyzer (TruMac CN Analyzer, Leco, USA).

2.4 Physical properties of the soil

Composite soil sample were packed and compacted in the soil core ring to three soil BD (0.14 g cm^{-3}, 0.18 g cm^{-3} and 0.22 g cm^{-3}). To achieve the desired soil BD, soil sample were weighed according to the following equation;

$$\mathrm{SoilBD}\left(\mathrm{g\ cm^{-3}}\right) = \frac{\mathrm{Soil\ dryweight\ (g)}}{\mathrm{Volumeofcorering(cm^{3})}} \tag{1}$$

To convert the dry weight basis to air-dried basis, soil dry weight is multiplied by moisture factor (MF). MF were calculated as follows:

$$\mathrm{MF} = \frac{\text{Weight of air dried soil (g)}}{\text{Weight of dried soil at } 105^{\circ}C\text{ (g)}} \tag{2}$$

Soil core ring was then transferred into three-phase meter (Daiki) for soil and air volume determination. The caps of the core ring were removed, and the bottom aperture were covered with nylon cloth before it was soaked 24 h in water for saturation process. The saturated core sample was then transferred into a box and the excess gravitational water was left to drain for about 24–48 h. The top aperture of the core ring was covered with the cap and the box containing the core sample was sealed to prevent evaporation. Core sample was weighed after 24 and 48 h to quantify the moisture content at field capacity. Then, the core sample were oven-dried at 105 °C for 24 h to determine the dry weight of the soil at each soil BD. Total porosity and volumetric moisture content, Θ_v, were calculated as follows;

$$Total\, porosity = 1-(BD/PD) \times 100 \tag{3}$$

where BD is the bulk density and PD is the particle density

$$\text{Volumetric moisture content} = \theta\mathrm{g}(\mathrm{BD}/\mathrm{WD}) \tag{4}$$

where Θg is the gravimetric moisture content and WD is the water density.

2.5 Incubation experiment

Soil CO_2 and CH_4 flux from each soil BD were determined by incubating the soil column under controlled laboratory condition (Fig. 2). Air-dried soil sample were packed in the PVC pipes, and soil samples were weighed according to each soil BD using Eq. (1). Each PVC pipe had an inner diameter of 83 mm, length of 200 mm and inner volume of 1080 cm^3. Three soil-packed pipes and an empty pipe were connected in a series using PVC sockets. Polyethylene filter soaked in 1% HCl solution overnight and rinsed with distilled water was placed at the bottom of the lowest soil-packed pipes. A layer of plastic net (1 mm mesh) was used to cover the bottom of PVC pipe, preventing soil from dropping. Then, the bottom part was connected to a PVC cap filled with cleaned quartz sand and distilled water. Quartz sand was soaked with 1% HCl solution overnight, rinsed with distilled water and combusted at 450 °C for 6 h before used.

At the bottom of the PVC cap, small holes were drilled to install a 5-cm PVC pipe for connecting a silicon tube to control the water level. The tubing was tied at the height of 50 cm (below soil surface) to imitate the groundwater table level at field condition. Redox potential (E_h) probes were installed horizontally at depth of 10 cm from soil surface in the column. The empty pipe above the soil was fitted with a flange for collecting the gas samples. During the incubation period, artificial rain event was simulated by spraying approximately 150 mL of filtered rainwater every three and a half day to maintain the soil moisture. The amount of rainwater added was based on the annual mean precipitation recorded at the sampling site which is 2575 mm from 2011 to 2016. The three different soil BD pipes were set in three replicates.

Soil CO_2 and CH_4 fluxes were measured on a weekly basis for 12 weeks. A PVC disk (having the same diameter as the flange) was placed on the flange and fixed using

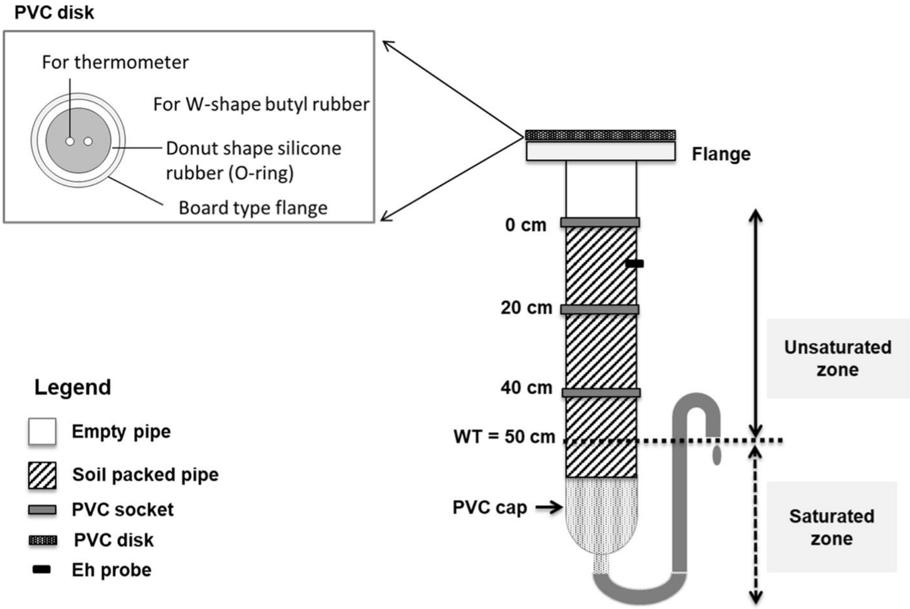

Fig. 2 Experimental design setup

four paper clips. The disk has two holes near the center and a donut-shape silicone rubber adhered to the bottom. A thermometer was inserted to one of the two holes beforehand. After the plate was fixed, a W-shape butyl rubber stopper was put into the second hole. Then, the gas inside the pipe was collected into 15-mL vacuumed vials through the W-shape stopper using a 25-ml syringe. Collection of gas samples was repeated four times at a 10-min interval. The gas samples were measured using gas chromatograph (GC) with a thermal conductivity detector (6890 N, Agilent, Santa Clara, CA, USA) for CO_2 detection and flame ionization detector (7890A, Agilent) for CH_4 detection.

Soil E_h was recorded at weekly interval after the gas sampling process using permanently installed platinum (Pt) electrode and voltmeter (Fiedler and Sommer 2004). Prior to installation, the Pt electrodes were checked using a standard redox solution (ZoBell's solution). All E_h data were corrected for the standard H electrode by adding 207 mV to the recorded readings (Niedermeier 2007). Temperature correction was not considered necessary as the experiment was performed under controlled laboratory condition with small temperature variation over the study period.

2.6 Statistical analysis

Data were analyzed using Statistical Analysis System (SAS) version 9.4 (SAS Institute Inc., Cary, NC, USA). Two-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) test was used to analyze the difference in measured parameters (soil porosity, moisture content and gas fluxes) among the three soils BD. Statistical considerations were based on $P \leq 0.05$ significant levels.

Table 2 Chemical properties of peat soil samples

Parameter	Average value
Types of peat	Hemic peat
Von Post Scale (humification level)	H5 to H6
pH (1:2.5)	3.3 ± 0.01*
Loss on ignition, LOI (%)	99 ± 0.03*
Total carbon (%)	59 ± 0.10*
Total nitrogen (%)	1.2 ± 0.02*
C/N ratio	50 ± 0.71*

*Average ± standard deviation

Table 3 Total porosity and volumetric moisture content at field capacity

Soil BD (g cm^{-3})	Total porosity (%)	Volumetric moisture content (%)	
		24-h drain	48-h drain
0.14	91 ± 0.5 *a*‡	71 ± 4.1 *b*	64 ± 0.6 *b*
0.18	87 ± 0.7 *b*	75 ± 1.2 *ab*	74 ± 4.3 *a*
0.22	83 ± 0.3 *c*	81 ± 1.1 *a*	80 ± 1.2 *a*

Average ± standard deviation. ‡ Values followed by different letter (within column) significantly differ at $P \leq 0.05$

3 Results

3.1 Chemical properties of peat soils

The sample was classified into the hemic group, ranging from H5 to H6 according to the Von Post Scale classification system (Table 2). The description suited the classification made as the samples were moderately decomposed and about one-third of the peat escapes between the fingers upon squeezing. The chemical properties of the peat soil used in this study showed a pH value of 3.3 and loss on ignition of 99%, indicating high acidity and high organic matter content. Total C content was higher while total N content was lower than the value reported from the previous study using peat soils from Mixed Peat Swamp forest (Sangok et al. 2017).

3.2 Physical properties of the soil

The total porosity was larger ($P \leq 0.05$) in the order of soil BD 0.14 g cm^{-3}, BD 0.18 g cm^{-3} and BD 0.22 g cm^{-3} (Table 3). The amount of moisture content held in the soil after the excess gravitational water allowed to drain freely (for 24 and 48 h) after saturation were greater ($P \leq 0.05$) at soil BD 0.22 g cm^{-3}, followed by 0.18 g cm^{-3} and BD 0.14 g cm^{-3}.

3.3 *Soil CO_2 flux*

Soil CO_2 fluxes were significantly affected by the soil BD ($P \leq 0.05$, Table 4) and showed significant changes with incubation time ($P \leq 0.05$). Contrary to linear pattern shown at BD

Table 4 Two-way analysis of variance (ANOVA) for CO_2 and CH_4 flux

Source of variation	CO_2 flux			CH_4 flux	
	DF	*F-value*	*P-value*	*F-value*	*P-value*
Soil BD	2	20.48	< 0.001*	6.70	0.002*
Time	12	9.61	< 0.001*	7.33	< 0.001*
Soil BD x time	24	6.24	< 0.001*	3.66	< 0.001*

*indicates significant difference at $P \leq 0.05$

0.14 g cm^{-3} ($r = 0.65$) and 0.18 g cm^{-3} ($r = 0.81$), soil CO_2 flux at BD 0.22 g cm^{-3} exhibited quadratic relationship with time ($r = 0.61$), which was characterized by low initial emission rates (week 0–4), rising slightly during the middle (week 5–8) and decreasing at the end of incubation period (week 9 to 12; Fig. 3). Total soil CO_2 flux for the 12-week period (Table 5, Fig. 4) was significantly larger ($P \leq 0.05$) at soil compacted to BD 0.22 g cm^{-3} and BD 0.18 g cm^{-3} compared to uncompacted soil BD 0.14 g cm^{-3}. However, higher soil CO_2 flux at the most compacted soil column was only observed during the early stages of incubation (week 0–8). At the later stage of incubation (week 9–12), total soil CO_2 flux from BD 0.22 g cm^{-3} was lower than BD 0.14 and 0.18 g cm^{-3} (Fig. 4).

3.4 *Soil CH_4 flux*

The CH_4 flux ranged from 57.76 to 393.16 µg C m^{-2} h^{-1}, −38.56 to 342.67 µg C m^{-2} h^{-1} and 40.90 to 355.34 µg C m^{-2} h^{-1}, for the soil BD 0.14, 0.18 and 0.22 g cm^{-3}, respectively (Fig. 3). Unlike soil CO_2 flux, there were no clear patterns observed for CH_4 fluxes between the soil BDs, partly because of the higher variability throughout the measurement periods. The coefficient variations within treatments sometimes exceed 40% particularly during the first two weeks incubation periods. This phenomenon was generally observed in CH_4 emission studies particularly in soil column experiments (Susilawati et al. 2016). A two-way analysis of variance (Table 4) demonstrates significant effects of both soil BDs and incubation time on CH_4 fluxes. Total soil CH_4 fluxes for 12 weeks of incubation (Table 5, Fig. 4) were significantly higher ($P \leq 0.05$) at uncompacted soil BD 0.14 g cm^{-3} than compacted soil to BD 0.18 and 0.22 g cm^{-3}.

3.5 *Redox potential (E_h)*

E_h from each soil BD varied markedly during the study period (Fig. 3) ranging from 700 to 160 mV which were within the normal E_h range found in natural conditions that supports major biogeochemical processes. Soil E_h at BD 0.14 g cm^{-3} and 0.18 g cm^{-3} recorded consistent value from the first measurement until the end of the incubation period. During the entire incubation period, E_h values remained between 520 and 670 mV indicating oxidized conditions according to the E_h classification system adopted by Mansfeldt (2003). Meanwhile, E_h value at soil BD 0.22 g cm^{-3} shifted to a less oxidizing environment over time resulting in decreased redox potential starting from week five until the end of incubation period. No significant correlations were observed between E_h with both CO_2 flux ($r = 0.20$–0.29) and CH_4 flux ($r = 0.06$–0.24) at three soil BD.

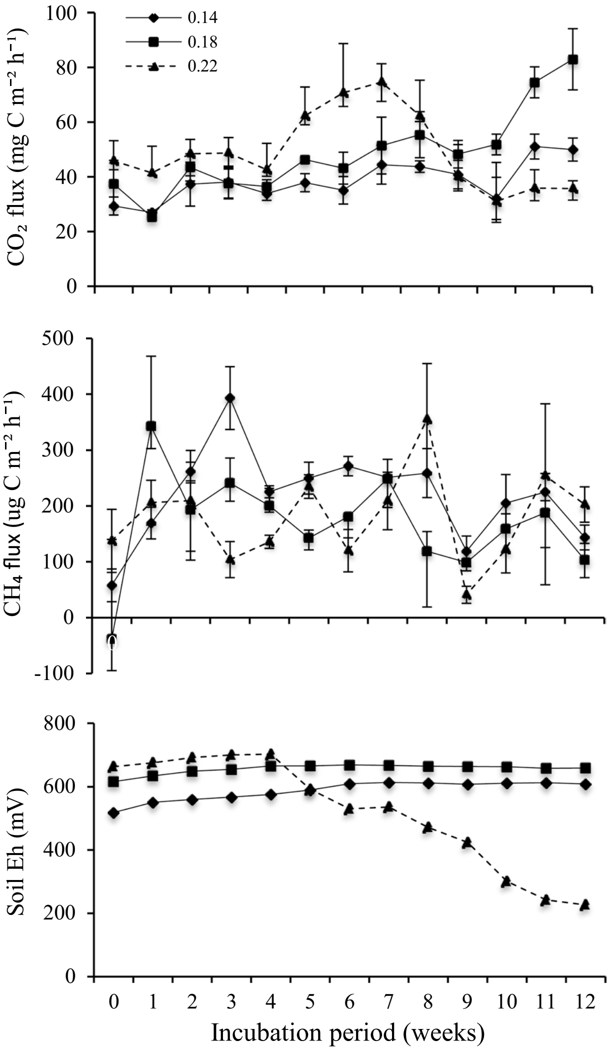

Fig. 3 Weekly variation in CO_2 fluxes, CH_4 fluxes and redox potential from three soil BD

Table 5 Average and total soil CO_2 and CH_4 fluxes for soil BD 0.14, 0.18 and 0.22 g cm^{-3}

Soil BD (g cm^{-3})	CO_2 flux (mg C m^{-2} h^{-1})	CH_4 flux (ug C m^{-2} h^{-1})	Total CO_2 flux (g C m^{-2})	Total CH_4 flux (mg C m^{-2})
0.14	38.50 ± 0.80 *b*‡	217 ± 15 *a*	77.42 *b*	461 *a*
0.18	48.77 ± 2.80 *a*	167 ± 49 *b*	96.39 *a*	360 *b*
0.22	49.20 ± 3.33 *a*	179 ± 35 *b*	100.58 *a*	363 *b*

Average ± standard deviation. ‡ Values followed by different letter (within column) significantly differ at *P ≤ 0.05*

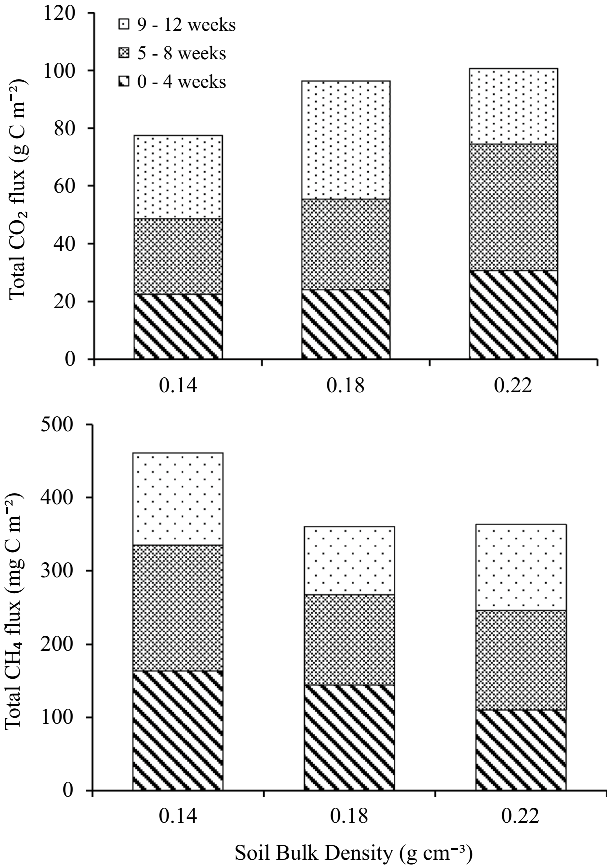

Fig. 4 Total fluxes of CO_2 and CH_4 for 12-week period of incubation

4 Discussion

4.1 Physical properties of the soil

Total porosity of peat soil decreased with the increased in soil bulk densities. Soil compacted to BD 0.18 g cm^{-3} and 0.22 g cm^{-3} reduced the total porosity by 4% and 9%, respectively. Although the reduction in total porosity with compaction was small, which is less than 10%, the pore size distribution is the relative proportion of macropore and micropore, among different soil BD may vary greatly. This phenomenon has been reported by Verry et al. (2011), in which the small variation in total porosity (84–97%) has greater variation in terms of pore size distribution.

Generally, compaction reduces the amount of macropores, leading to higher soil BD and greater proportion of micropores in compacted compared to non-compacted soil. Although in this study, a number of macropores and micropores were not measured, the results from volumetric moisture content can be used as an indication of pore size distribution (Thompson and Waddington 2013; Kurnain et al. 2019). According to Lipiec

(2009), the higher volumetric moisture content in compacted soil indicates greater proportion of smaller pores which can retain more water.

Our results showed that volumetric moisture content increased with increasing soil BD. This implies that compaction on peat soil can increase the water retention capacity of peat, which is critical to the effective management of such soils from agricultural perspectives. Water management in peatland for oil palm cultivation should maintain higher water retention (Melling and Hatano 2010) and keeping the soil moist until the top layer is important to minimize peat oxidation (Othman et al. 2009) and improve the growth and production of oil palm (Ginting et al. 2016).

4.2 Soil CO_2 flux

The reduction in soil porosity and increase in moisture retention with compaction were expected to reduce the soil C emission from compacted peat. However, total soil CO_2 flux for 12 weeks incubation was larger at compacted than uncompacted soil. This is most probably due to the changes in water infiltration rate over the course of the 12 weeks of incubation. Water infiltration rates after the artificial rain event was faster at uncompacted soil, where rainwater percolates down the soil column instantly upon addition. This observation is in accordance with previous finding (Ritzema 2007; Hairiah et al. 2020) that showed high infiltration capacity and drainable pore space in undisturbed peat swamp forest. Infiltration and percolation rates of water are reduced following the land conversion from the primary forest to an oil palm plantation when soils are compacted by heavy machinery (Comte et al. 2012).

Slower infiltration and percolation of rainwater at compacted soil, generally, can be associated with the greater proportion of small pore space. In addition, greater moisture retention at compacted soil possibly restricts the water flow in the soil column. This causes the temporary surface waterlogging at soil column BD 0.18 and 0.22 g cm^{-3} after rain event. However, it should be noted that in oil palm plantation, once rainfall reaches land surface in the field, it either infiltrates into the soil or can run off over the soil surface as overland flow (Comte et al. 2012). Therefore, surface waterlogging will not likely to happen more than one day. The existing of oil palm roots will improve water infiltration in the plantation (Ahmad et al. 2012). In addition, the design of incubation study that makes the soil BD uniform throughout the soil column caused water percolation down the soil column profile slower than what normally observed in the field condition.

Surface waterlogging occurred after the rain event, possibly entrapping the gas in the soil pore space. Higher soil CO_2flux recorded at compacted soil was most likely due to the physical displacement of stored CO_2 in the pore space prior to the gas sampling period. Similar results have also been reported by Pla et al. (2017) where higher production of CO_2 concentration after rainfall event was attributed to the low infiltration rates and hydraulic conductivity at the study site.

The effect of water infiltration on soil CO_2 fluxes changes when the soil pore spaces started to become saturated with water and soil CO_2 fluxes were mainly limited by O_2. This was observed at soil column with BD of 0.22 g cm^{-3}, in which CO_2 flux declined during the last four weeks of the incubation period (Fig. 3). At this particular time, soil oxygenation status shifted from aerobic (400–700 mV) to anaerobic condition (180–300 mV), which resulted in low CO_2 flux. According to Inglett et al. (2005) + 300 mV is the break point between aerobic and anaerobic condition, with E_h above + 300 mV being regarded as aerobic and below + 300 mV as anaerobic condition. $E_h < 250$ mV is also generally associated with the exhaustion of O_2.

4.3 Soil CH4 flux

On the contrary, there was no evidence observed in this study that can relate CH_4 fluxes to the changes in water infiltration rates. In addition, CH_4 fluxes showed the opposite pattern than those in CO_2 fluxes, with the total soil CH_4 fluxes being significantly higher ($P \leq 0.05$) at uncompacted soil than compacted soil. This result is also consistent with other studies that reported the reduction of CH_4 emission in compacted soil (Ball et al. 1997; Mosquera et al. 2007). A contrasting suggestion, however, was made by Murdiyarso et al. (2010), which hypothesized the increase in the soil CH_4 fluxes after peat soil compaction. As compaction resulted in the increase in water content and favors the anaerobic condition, this enhanced the methanogenic activity and simulated the increased in CH_4 production rates (Nawaz et al. 2013).

Nevertheless, it was observed in this study that even when the soil column at BD 0.22 g cm^{-3} started to be saturated with water and shifted to a more anaerobic condition, there is no significant changes observed in the soil CH_4 flux. One of the possible reasons is because the amount of CH_4 emitted from peat soil depends on the balance between CH_4 production, consumption as well as its transport mechanism. According to Frey et al. (2011), decrease in infiltration capacity, air permeability and gas diffusion after soil compaction influenced the balance between these three processes. The results of this study suggested that although the CH_4 production rates may increase during anaerobic condition, reduction in gas diffusion due to higher BD and lower soil porosity in compacted soil possibly leads to reduction in soil CH_4 emitted from the soil.

5 Conclusions

Our results show that compaction strongly affects soil porosity, moisture retention and soil C emission from tropical peatlands. Compacted peat tends to maintain a higher moisture content than uncompacted peat, which reduces soil aeration and reduces CH_4 emission. On the contrary, soil CO_2 flux was greater at the compacted peat due to the physical displacement of accumulated CO_2 in pore space when rainwater slowly infiltrates and percolates through soil column. This implies that the infiltration and water flow in peat soils especially prior to the gas sampling can influence the results. Thus, it is highly important to pay attention to the timing of the gas sampling that coincides with rainfall when evaluating the effects of mechanical compaction on soil C emission in the future study. It is recommended to conduct continuous gas measurement instead of one-time sampling. In addition, soil column conditions limited by the uniform soil BD throughout the soil depth did not fully represent field condition. BD of peat soil in the field condition typically varies with the peat depth. Therefore, further improvement in the experimental setup is recommended.

Acknowledgements This research was supported by Sarawak State Government and Putra Grant for graduate student Universiti Putra Malaysia (No. GP: IPS/2018/9611500). The authors wish to thank staff members of Sarawak Tropical Peat Research Institute especially Mr. Mohd. Zulhilmy and Dr. Faustina Sangok for technical and scientific assistance during laboratory incubation setup and discussion session. The authors also wish to convey their appreciation to Mr. Donny Sudid (Soil Branch, DOA) for his expertise and valuable assistance during the kick-off of the experiment

References

Ahmad, N. F. A. (2012). Field evaluation of infiltration models under oil palm plantation with reference to stemflow & througfall areas (Doctoral dissertation, Universiti Teknologi Malaysia).

Andersen, R., Grasset, L., Thormann, M. N., Rochefort, L., & Francez, A. J. (2010). Changes in microbial community structure and function following Sphagnum peatland restoration. *Soil Biology and Biochemistry, 42*(2), 291–301.

Anderson, J. A. R. (1964). The structure and development of the peat swamps of Sarawak and Brunei. *Journal of Tropical Geography, 18,* 7–16.

Ball, B. C., Dobbie, K. E., Parker, J. P., & Smith, K. A. (1997). The influence of gas transport and porosity on methane oxidation in soils. *Journal of Geophysical Research: Atmospheres, 102*(D19), 23301–23308.

Beare, M. H., Gregorich, E. G., & St-Georges, P. (2009). Compaction effects on CO_2 and N_2O production during drying and rewetting of soil. *Soil Biology and Biochemistry, 41*(3), 611–621.

Comte, I., Colin, F., Whalen, J. K., Grünberger, O., & Caliman, J. P. (2012). Agricultural practices in oil palm plantations and their impact on hydrological changes, nutrient fluxes and water quality in Indonesia: a review. *Advances in Agronomy, 116,* 71–124.

Deboucha, S., Hashim, R., & Alwi, A. (2008). Engineering properties of stabilized tropical peat soils. *Electronic Journal of Geotechnical Engineering, 13,* 1–9.

Fiedler, S., & Sommer, M. (2004). Water and redox conditions in wetland soils, their influence on pedogenic oxides and morphology. *Soil Science Society of America Journal, 68*(1), 326–335.

Firdaus, M. S., Seca, G. and Ahmed, O. H. (2011). Effect of drainage and land clearing on selected peat soil physical properties of secondary peat swamp forest. *International Journal of Physical Sciences*, *6*(23), pp. 5462–5466.

Frey, B., Niklaus, P. A., Kremer, J., Lüscher, P., & Zimmermann, S. (2011). Heavy-machinery traffic impacts methane emissions as well as methanogen abundance and community structure in oxic forest soils. *Applied and Environment Microbiology, 77*(17), 6060–6068.

Ginting, E. N., Nuzul, H. D., & Winarna. (2016). Effective water management for oil palm in Peatland: For peat conservation and yield optimization. *Proceeding of International Peat Congress, 61,* 497–501.

Hairiah, K., van Noordwijk, M., Sari, R. R., Saputra, D. D., Suprayogo, D., Kurniawan, S., & Gusli, S. (2020). Soil carbon stocks in Indonesian (agro) forest transitions: Compaction conceals lower carbon concentrations in standard accounting. *Agriculture, Ecosystems & Environment, 294,* 106879.

Hodgkins, S. B., Richardson, C. J., Dommain, R., Wang, H., Glaser, P. H., Verbeke, B., & Flanagan, N. (2018). Tropical peatland carbon storage linked to global latitudinal trends in peat recalcitrance. *Nature communications, 9*(1), 1–13.

Inglett, P. W., Reddy, K. R., & Corstanje, R. (2005). *Encyclopedia of soils in the environment* (pp. 72–78). London: Academic Press.

Kolay, P. K., & Pui, M. P. (2010). Peat stabilization using gypsum and fly ash. *Journal of Civil Engineering, Science and Technology, 1*(2), 1–5.

Könönen, M., Jauhiainen, J., Laiho, R., Kusin, K., & Vasander, H. (2015). Physical and chemical properties of tropical peat under stabilised land uses. *Mires and Peat, 16*(8), 1–13.

Kurnain, A. (2019). Hydrophysical properties of ombrotrophic peat under drained peatlands. *International Agrophysics 33,* 277–283.

Lipiec, J., Wojciga, A., & Horn, R. (2009). Hydraulic properties of soil aggregates as influenced by compaction. *Soil and Tillage Research, 103*(1), 170–177.

Mansfeldt, T. (2003). In situ long-term redox potential measurements in a dyked marsh soil. *Journal of Plant Nutrition and Soil Science, 166*(2), 210–219.

Melling, L., Chua, K.H. and Lim, K.H. (2008). Managing peat soils under oil palm. In *Agricultural Crop Trust 2008, Agronomic Principles and Practices of Oil Palm Cultivation, Sibu, Sarawak, 13th–16th October, 2008, p. 485.*

Melling, L., & Hatano, R. (2010). Sustainable utilization of tropical peatland for oil palm plantation. In *Proceeding of Palangkaraya International Symposium & Workshop On Tropical Peatland.*

Melling, L. (2016). Peatland in Malaysia. In M. Osaki & N. Tsuji (Eds.), *Tropical Peatland ecosystem* (pp. 59–74). Tokyo, Japan: Springer.

Monda, Y., Kiyono, Y., Chaddy, A., Damian, C., & Melling, L. (2018). Association of growth and hollow stem development in Shorea albida trees in a tropical peat swamp forest in Sarawak Malaysia. *Trees, 32*(5), 1357–1364.

Mosquera, J., Hol, J. M. G., Rappoldt, C., & Dolfing, J. (2007). Precise soil management as a tool to reduce CH_4 and N_2O emissions from agricultural soils. Report 28. Wageningen. 42 pp.

Murdiyarso, D., & Hergoualc'h, K., & Verchot, L. V. . (2010). Opportunities for reducing greenhouse gas emissions in tropical peatlands. *Proceedings of the National Academy of Sciences, 107*(46), 19655–19660.

Mohd-Azlan, J., & Das, I. (Eds.). (2016). Wildlife Conservation In Peat Swamp Forests. In *Biodiversity of tropical peat swamp forests of Sarawak* (pp. 209–227). Universiti Malaysia Sarawak.

Nawaz, M. F., Bourrie, G., & Trolard, F. (2013). Soil compaction impact and modelling. A review. *Agronomy for sustainable development, 33*(2), 291–309.

Niedermeier, A., & Robinson, J. S. (2007). Hydrological controls on soil redox dynamics in a peat-based, restored wetland. *Geoderma, 137*(3–4), 318–326.

Nusantara, R. W., Aspan, A., Alhaddad, A. M., Suryadi, U. E., Makhrawie, M., Fitria, I., et al. (2018). Peat soil quality index and its determinants as influenced by land use changes in Kubu Raya District, West Kalimantan Indonesia. *Biodiversitas Journal of Biological Diversity, 19*(2), 535–540.

Othman, H., Darus, F. M., & Mohammed, A. T. (2009). Experiences in peat development for oil palm planting in the MPOB research station at Sessang, Sarawak. *Oil Palm Bulletin, 58,* 1–13.

Padfield, R., Waldron, S., Drew, S., Papargyropoulou, E., Kumaran, S., Page, S., & Zakaria, Z. (2015). Research agendas for the sustainable management of tropical peatland in Malaysia. *Environmental Conservation, 42*(1), 73–83.

Page, S. E., Rieley, J. O., & Banks, C. J. (2011). Global and regional importance of the tropical peatland carbon pool. *Global Change Biology, 17*(2), 798–818.

Pla, C., Cuezva, S., Martinez-Martinez, J., Fernandez-Cortes, A., Garcia-Anton, E., Fusi, N., et al. (2017). Role of soil pore structure in water infiltration and CO_2 exchange between the atmosphere and underground air in the vadose zone: A combined laboratory and field approach. *CATENA, 149,* 402–416.

Reichert, J. M., Suzuki, L. E. A. S., Reinert, D. J., Horn, R., & Håkansson, I. (2009). Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. *Soil and Tillage Research, 102*(2), 242–254.

Ritzema, H. P. (2007). The role of drainage in the wise use of tropical peatlands. In Carbon-climate-human interaction on tropical Peatland. Proceedings of the *International Symposium and Workshop on tropical Peatland, Yogyakarta, Indonesia* on 27–29 August 2007 (pp. 9–9).

Rothwell, R. L., Silins, U., & Hillman, G. R. (1996). The effects of drainage on substrate water content at several forested Alberta peatlands. *Canadian Journal of Forest Research, 26*(1), 53–62.

Sangok, F. E., Maie, N., Melling, L., & Watanabe, A. (2017). Evaluation on the decomposability of tropical forest peat soils after conversion to an oil palm plantation. *Science of The Total Environment, 587,* 381–388.

Sangok, F. E., Sugiura, Y., Maie, N., Melling, L., Nakamura, T., Ikeya, K., & Watanabe, A. (2020). Variations in the rate of accumulation and chemical structure of soil organic matter in a coastal peatland in Sarawak Malaysia. *CATENA, 184,* 104244.

Sarawak foresty corporation 2013.http://www.sarawakforestry.com.

Soane, B. D., & Van Ouwerkerk, C. (1994). Soil compaction problems in world agriculture. In *Developments in Agricultural Engineering* (Vol. 11, pp. 1-21). Elsevier.

Susilawati, H. L., Setyanto, P., Ariani, M., Hervani, A., & Inubushi, K. (2016). Influence of water depth and soil amelioration on greenhouse gas emissions from peat soil columns. *Soil science and plant nutrition, 62*(1), 57–68.

Thompson, D. K., & Waddington, J. M. (2013). Peat properties and water retention in boreal forested peatlands subject to wildfire. *Water Resources Research, 49*(6), 3651–3658.

Verry, E.S., D.H. Boelter, J. Paivanen, D.S. Nichols, T. Malterer & A. Gafni. (2011). Physical properties of organic soils. In: Kolka, R., S. Sebestyen, E.S. Verry & K. Brooks (Eds.). *Peatland Biogeochemistry and Watershed Hydrology at the Marcell Experimental Forest,* 135–176.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.