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# Evaluation on the decomposability of tropical forest peat soils after conversion to an oil palm plantation

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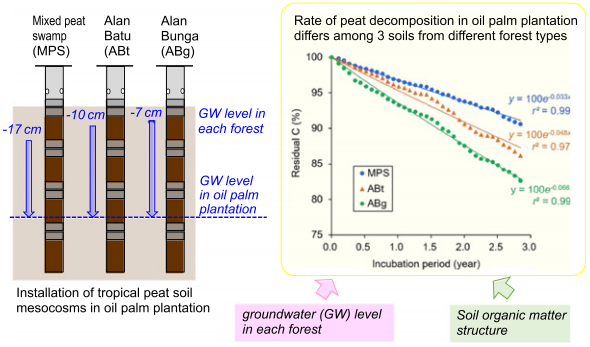
## HIGHLIGHTS

- The effects of changes in groundwater table towards the decomposition of SOM material in peat soils.
- C stability in the peat SOM after reclamation to oil palm plantation through 3-year monitoring of $CO_2$ and $CH_4$ fluxes.
- C composition estimated from 3 forest types, in relation with $CO_2$ fluxes cause the differences of decomposition rates.

## GRAPHICAL ABSTRACT




The differences of groundwater table level in each forest and soil organic matter structure resulting in the differences of decomposition rates of peat SOM in an oil palm plantation.

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## ABSTRACT

To understand the variations in the decomposability of tropical peat soil following deforestation for an oil palm plantation, a field incubation experiment was conducted in Sarawak, Malaysia. Peat soils collected from three types of primary forest, namely Mixed Peat Swamp (MPS; *Gonystylus-Dactylocladus-Neoscrotechinia* association), Alan Batu (ABt; *Shorea albida-Gonstylus-Strenonurus* association), and Alan Bunga (ABg; *Shorea albida* association), were packed in polyvinyl chloride pipes and installed in an oil palm plantation. Carbon dioxide ($CO_2$) and methane ($CH_4$) fluxes from soil were monthly measured for 3 years. Environmental variables including soil temperature, soil moisture content, and groundwater table were also monitored. The pH, loss on ignition, and total carbon (C) content were similar among the three soils, while total N content was larger in the MPS than in the ABg soils. Based on $^{13}C$ nuclear magnetic resonance (NMR) spectroscopy, C composition of the MPS and ABg soils was characterized by the largest proportion of C present as alkyl C and *O*-alkyl C, respectively. The C composition of the ABt soil was intermediate between the MPS and ABg soils. The $CO_2$ fluxes from the three soils ranged from 78 to 625 mg C $m^{-2}$ $h^{-1}$ with a negative correlation to groundwater level. The $CH_4$ fluxes ranged from −67 to 653 μg C $m^{-2}$ $h^{-1}$. Both total $CO_2$ and $CH_4$ fluxes were larger in the order ABg > ABt > MPS ($P < 0.05$). Annual rate of peat decomposition as was estimated from cumulative C loss differed up to 2 times, and the rate constant in exponential decay model was 0.033 $y^{-1}$ for the MPS soil and 0.066 $y^{-1}$ for the ABg soil. The field incubation results of the three forest peat soils seem to reflect the difference in the labile organic matter content, represented by polysaccharides.



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## 1. Introduction

Globally, tropical peatland area is estimated to be $4.41 \times 10^5$ km$^2$, of which 56% is distributed in Southeast Asia (Page et al., 2011). In Malaysia, peatlands occupy an area of about $2.7 \times 10^4$ km$^2$ (Mutalib et al., 1992), with $1.7 \times 10^4$ km$^2$ of them in Sarawak (Tie and Kueh, 1979). In Southeast Asia, peat deposits accumulate up to 20 m thickness, which stores 68.5 Pg of carbon (C) (Page et al., 2011). Development of peat accumulation is resulted from a fine balance of hydrology, ecology, and landscape morphology (Page et al., 1999). If this balance is disturbed, the rate of peat decomposition would become higher than that of peat accumulation.

Carbon storage capacity of peatland ecosystem is influenced by land use change (Hergoualc'h and Verchot, 2011). Since 1990s, about 25% of the peatland area in Malaysia has been converted to oil palm plantations (Lim et al., 2012), in which drainage, compaction, and groundwater table control are prerequisites. Drainage creates an oxic zone for a better root respiration, while compaction increases soil bulk density and soil surface load-bearing capacity and improves the capillary rise resulting in a higher soil moisture content above the groundwater table. Drainage has been suggested to accelerate soil organic matter (SOM) decomposition (Murayama and Bakar, 1996) and affects carbon dioxide ($CO_2$) and methane ($CH_4$) fluxes from soil (Inubushi et al., 2003; Jaenicke et al., 2008). The level of oxidation induced by drainage might be affected by the extent of soil compaction which could change the size distribution of soil pore space.

As $CH_4$ is produced exclusively under anaerobic conditions, groundwater level and water filled pore space are among the most important factors influencing the $CH_4$ flux from tropical peat soil (Melling et al., 2005b; Watanabe et al., 2009). Although soil temperature is also important for both of $CH_4$ and $CO_2$ fluxes, soil moisture condition is likely more important even for $CO_2$ flux in the tropics because of a high and narrow range of soil temperature (Melling et al., 2005a; Hirano et al., 2014; Marwanto and Agus, 2014).

Most of tropical peatlands are located and developed at low altitude swamp forests. Due to the influence of peat hydrology, the topography of peatland in Southeast Asia generally develops to dome shape, leading to the formation of different phasic communities from the edge to the center (Anderson, 1964). Peat swamp forests in Sarawak are classified into 6 phasic communities of MPS (*Gonustylus-Dactylocladus-Neoscortechinia* association), Alan (*Shorea albida* association), Padang Alan (*Shorea albida-Litsea-Parastemon* forest association), Padang Selunsur (*Tristania-Parastemon-Palaquim* forest association), and Padang Keruntum (*Combretocarpus-Dactylocladus* forest association; Anderson, 1964; Phillips, 1998). Alan forest is further classified into Alan Batu (ABt; *Shorea albida-Gonystylus-Stemonurus* association) and Alan Bunga (ABg; *Shore albida* association) forests depending on the morphology of the trees. These two Alan forests and MPS are the most common forest type in Sarawak (Melling, 2016). As MPS forest is generally located at the lower elevations of the peat dome, receiving water and nutrients from a larger area of upslope, species composition is richer and peat soil is less woody. Peat soils in ABt and ABg forests are more woody. ABg forest is commonly found towards the peat dome ABt forest is found in a more stressful environment at the shoulder of the peat dome, where the hydrological movement of water from the center to the edge of peat dome is more vigorous. Such harsh environmental conditions of ABt forest result in the physiological adaptation of *Shorea albida* by having bigger buttresses compared to that in ABg forest. The roots are also more extensive, resulting in vacant layers with 20–30 cm thickness within the top 100 cm layer of soil (Melling, 2016). The details of the different phasic communities in tropical peat swamp forest can be found in Melling (2016) and the illustration of the three representative forests is shown in SI Fig. 1 (Anderson, 1961).

The objective of the present study was to evaluate the SOM decomposability of tropical peat soils developed in different phasic communities after conversion to an oil palm plantation. Due to the complexity in the influence of land use change on peat soil conditions, we focused the effect of drainage on the rate of peat C decomposition to $CO_2$ or $CH_4$. To simulate the situation, peat soils collected from three different primary phasic communities were installed in an oil palm plantation, and $CO_2$ and $CH_4$ fluxes were monitored for 3 years. To determine the factors that affect the peat decomposition rate, environmental variables were also monitored. The effect of chemical structure of SOM on the rate of decomposition was discussed with regard to the C composition of initial soil samples that was analysed using solid-state $^{13}$C nuclear magnetic resonance (NMR) spectroscopy.

## 2. Materials and methods

### 2.1. Peat soil samples

Peat soil samples were collected in the Maludam National Park, Sarawak, Malaysia, in August 2012 (Fig. 1). The Maludam National Park covers an extensive area of 430 km$^2$ and comprises one of the largest peat domes in Borneo (Melling, 2016). Annual mean precipitation and daily mean air temperature at the Maludam National Park in 2011–2014 were 2770 mm and 26.9 °C, respectively. Soil samples were collected in MPS, ABt, and ABg forests. The MPS forest had structure and physiognomy similar to the lowland dipterocarp rainforest on mineral soils and uneven canopy of 40–45 m height. The ABt forest showed the signs of decaying trees, including staghead crowns, hollow stems, and heavily buttressed boles, and had irregular and uneven canopy of 50–55 m. Trees in the ABg forest had lower and narrower buttreses compared to those in the ABt forest and consisted even upper canopy of 45–50 m. Major plant species as well as environmental variables are presented in Table 1. At two points with a 200-m apart from the environmental variables monitoring stations, which were installed in the center of each forest, soil samples were taken as blocks using a chainsaw. To observe the effect of drainage on the rate of SOM decomposition, 20–40 cm depth layer samples which may have experienced aerobic conditions very rarely for a long period were collected by cutting away the 0–20 cm and >40 cm layers. Then the soil samples were mixed thoroughly to make a composite sample.

### 2.2. Field incubation experiment

Peat soil samples were immediately transferred to an oil palm plantation in Sibu, Sarawak (2° 09′ N, 111° 53′ E; peat thickness, 8–11 m; previous vegetation, MPS forest), which was established in 2007. The soil samples collected from the same vegetation were thoroughly mixed with removing large debris, and then soil mesocosms were prepared as follows (SI Fig. 2): Composite samples (700–800 g) were packed in polyvinyl chloride (PVC) pipes. Each PVC pipe had an inner diameter of 83 mm and length of 200 mm. These combinations gave the bulk density 0.16–0.18 g cm$^{-3}$, which are intermediate between natural forests and oil palm plantation and thus may express the transition state from forest to the plantation. A polyethylene filter was placed at the bottom of the pipe (inner volume, 1080 cm$^3$). Four soil-packed pipes and an empty pipe were connected in a series using sockets. The top empty pipe has a flange for fitting a plate when gas samples are collected and two lateral holes for supporting smooth gas exchange when gas samples are not collected. The bottom of the lowest pipe was covered with a plastic net (1-mm mesh) and the side of the connected pipes was wrapped with a high-density polyethylene film to strengthen the pipes connection. Then the mesocosms were buried in the field so that the soil surfaces were levelled between the inside and outside of the pipes. Three mesocosms packed with the soils from the three forests were installed at the same point with 1 m distance between each 2 pipes and 3–4 m distance from the nearest oil palm tree. In the plantation, oil palm roots are concentrated within the surface 50 cm layer (Lim et al., 2012) because those cannot respirate under flooded conditions. The incubation experiment was conducted in 5 replicates.

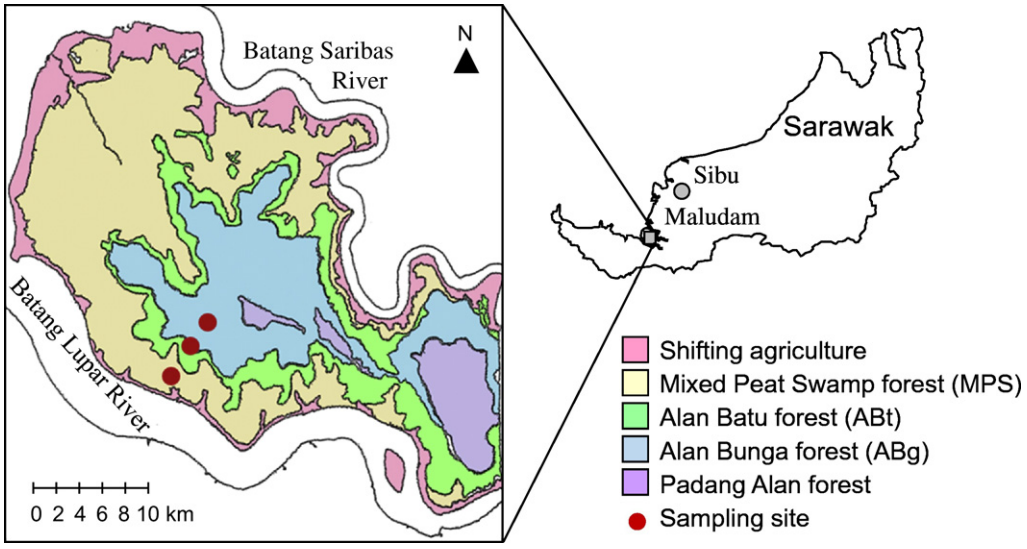


**Fig. 1.** Map of Sarawak, Malaysia, and location of soil sampling sites in the Maludam National Park (Melling, 2016).

The $CO_2$ and $CH_4$ fluxes and environmental variables were monitored once a month from October 2012 to August 2015. A PVC disk having the same diameter (180 mm) as the flange and 4 mm thickness was placed on the flange and fixed using 6 paper clips (SI Fig. 1). The disk has three holes near the center and a donut shape silicone rubber adhered to the bottom. A Tedlar® bag (bottom side) for controlling the inner pressure during gas sampling and a thermometer were inserted to two of the three holes beforehand. After the plate was fixed, a W-shape butyl rubber stopper was put into the third hole. The lateral holes of the uppermost pipe were also stopped up with butyl rubber stoppers. Then, the gas inside the pipe was collected into 15-mL evacuated vials through the W-shape stopper using a double-ended needle. Collection of gas sample was repeated three times at a 10 min interval. At the same time, soil temperature (a portable temperature probe, Checktemp1, Hanna, Woonsocket, RI, USA) and soil moisture (a TDR moisture meter, DIK-311F, Daiki, Saitama, Japan) at 5 cm depth were recorded. After gas collection, the plate and butyl rubber stoppers were removed. Groundwater table was measured using perforated PVC pipe. No weeds grew inside the pipes. The gas samples collected were brought back to the laboratory, and the concentrations of $CO_2$ and $CH_4$ were determined using gas chromatographs with a thermal conductivity detector (6890N, Agilent, Santa Clara, CA, USA) or flame ionization detector (7890A, Agilent), respectively.

In August 2015, each three mesocosms containing different kinds of soil samples were collected. No damage was observed in both the polyethylene film and PVC pipes. Soil samples collected from each compartment were freeze-dried, weighed, crushed, and measured for total C.

### 2.3. Characterization of SOM and analyses of soil physico-chemical properties

Chemical structure of SOM was characterized using solid-state $^{13}C$ NMR spectroscopy. Prior to analysis, the soil samples were freeze-dried and pulverized (<0.5 mm) A 30 mg sample was put into a 4 mmφ sample tube and ramp cross polarization/magnetic angle spinning (CPMAS) $^{13}C$ NMR spectra with phase-adjusted spinning side bands (PASS) sequence (Ikeya and Watanabe, 2016) were recorded at 176 MHz on ECA 700 spectrometer (JEOL, Tokyo, Japan). Operation conditions were as follows: contact time, 1.0 ms; spinning rate, 9 kHz; recycle delay, 1.0 s; and number of data accumulation, 2080–4160. The chemical shift was relative to tetramethylsilane (0 ppm) and adjusted with hexamethylbenzene (17.36 ppm). The spectra were divided into 5 regions of 0–45 (saturated alkyl C), 45–110 (*O*-alkyl C), 110–160 (aromatic C), 160–190 (carboxyl C), and 190–220 (ketone C) ppm, and cumulative signal intensities in each region relative to total were regarded as the relative abundance of each C functional group.

Soil pH ($H_2O$) was measured at the soil to water ratio of 2:5 (w/v) using a pH meter (Metrohm 827, Metrohm, Herisau, Switzerland). Loss on ignition was determined using a thermo gravimetric analyzer

**Table 1**
Principal information of 3 forests site in Maludam National Park.

| Forest type | Mixed Peat Swamp (MPS) | Alan Batu (ABt) | (ABg) |
|---|---|---|---|
| GPS point | 1° 25′ N, 111° 07′ E | 1° 27′ N, 111° 08′ E | 1° 27′ N, 111° 09′ E |
| Mean groundwater table (cm)[a] | | | |
| Dry season[b] | −20.7 | −11.0 | −7.6 |
| Wet season[c] | −13.3 | −9.3 | −6.9 |
| Mean soil temperature at 5 cm (°C)[a] | | | |
| Dry season | 25.9 | 26.7 | 27.3 |
| Wet season | 25.5 | 26.2 | 26.8 |
| Vegetation[d] | *Gonstylus bancanus*, *Dactylocladus stenostachys*, *Copaifera palustris*, and 4 species of *Shorea* with 120–150 tree species $ha^{-1}$. | Similar to MPS but dominated by scattered very large (>3.5 m girth) *Shorea albida*. | Entirely dominated by *Shorea albida* with 70–100 trees $ha^{-1}$. |

[a] The variables were recorded in the year of 2011–2014.
[b] From April to September.
[c] From October to March.
[d] Sources are Anderson (1961), Monda et al. (2015), and Melling (2016).

(TGA 701, Leco, St. Joseph, MI, USA). Total C and total nitrogen (N) contents were determined using a NC analyzer (Sumigraph NC-22, Sumica Chemical Analysis Service, Osaka, Japan).

### 2.4. Statistical analysis

Rate constant of soil organic carbon (SOC) decomposition was estimated by regressing cumulative $CO_2$-C fluxes to an exponential decay model. One-way ANOVA was used to analyse the difference in gas fluxes or rate of peat decomposition among the three peat soil samples. The significance of the difference between the forest types was determined using Fisher Least Significance Difference (LSD). Because of no replicate for the original soil samples, similar/different in soil chemical properties and C composition of SOM are based on the general levels of experimental errors in each analysis. In case of C composition, a >4% difference was enough to be regarded as different according to Watanabe et al. (2007).

## 3. Results

### 3.1. Characteristics of peat soils

There were no large differences in total C content and loss on ignition among the three peat soil samples, which were in the ranges of 520–535 g $kg^{-1}$ and 98–99%, respectively (Table 2). Total N content in the MPS soil (20 g $kg^{-1}$) was 1.5 times of that in the ABg soil, resulting in the C/N ratio higher in the order: ABg > ABt > MPS.

Fig. 2 shows the $^{13}C$ CP/PASS NMR spectra of the three soil samples. The chemical shifts of major resonance maxima were similar among the samples, i.e., 28–31 ppm for methylene C in alkyl chains, 54–55 ppm for methoxyl C, 61 ppm for primary alcohol C, 71–72 ppm for secondary alcohol C, and 103 ppm for acetal C, (these 3 peaks are derived mainly from polysaccharides), 128–130 ppm for aromatic C, 152 ppm for *O*-aryl C, and 171–173 ppm for carboxyl C. However, their relative intensities vary among the three samples, e.g., methylene C signals were the most intense signals in the MPS soil while the secondary alcohol C signals were the largest in both of the ABt and ABg soils. The methoxyl C and *O*-aryl C signals were larger in the spectra of the ABt and ABg soils, suggesting less degradation of lignin, compared to the MPS soil.

Table 3 shows the C composition as was estimated from the $^{13}C$ CP/PASS NMR spectra. The % *O*-alkyl C (26–37%) was larger in the order ABg, ABt, and MPS, and %aromatic C was also larger in the ABg soil (33%) than in the other two soils (27%). On the contrary, % alkyl C (21–33%) was larger in the order MPS, ABt, and ABg. The % carboxyl C also tended to be smaller in the ABg soil (9%) than in the other two soils (13%).

### 3.2. $CO_2$ and $CH_4$ fluxes from soil mesocosms

Fig. 3 shows the temporal variations in $CO_2$ and $CH_4$ fluxes from the three peat soils and those in the environmental variables. Throughout the 3-year period, soil temperature tended to be higher in the dry season (26.2–28.7 °C) than in the wet season (24.8–28.0 °C), and the annual mean soil temperature was 27.0–27.1 °C through the 3 years. Groundwater table tended to be higher in the wet season (−83.2 to 16.2 cm) than in the dry season (−99.0 to −20.8 cm), varying from year to year. Soil moisture content ranged from 54 to 84% and did not follow the variation in groundwater table.

**Table 2**
Physico-chemical properties of peat soil samples.

| Soil sample | pH ($H_2O$) | Loss on ignition (%) | Total C (g $kg^{-1}$) | Total N (g $kg^{-1}$) | C/N ratio |
|---|---|---|---|---|---|
| MPS | 3.6 | 98 | 535 | 20 | 27 |
| ABt | 3.7 | 99 | 523 | 16 | 33 |
| ABg | 3.6 | 99 | 520 | 13 | 40 |

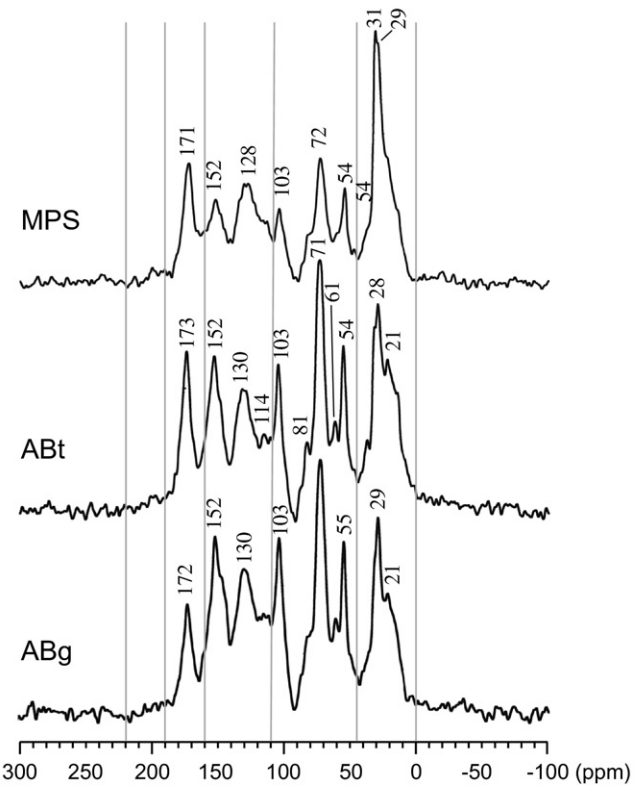


**Fig. 2.** $^{13}C$ CP/PASS NMR spectra of tropical peat soil samples from three forest types.

The $CO_2$ flux fluctuated from 95 to 480 mg C $m^{-2}$ $h^{-1}$, 78–592 mg C $m^{-2}$ $h^{-1}$, and 138–625 mg C $m^{-2}$ $h^{-1}$, for the MPS, ABt, and ABg soils, respectively (Table 4). The $CO_2$ flux from the ABt and ABg soils was correlated negatively to the groundwater table ($r = -0.525$ or $-0.597$; $P < 0.005$). Significant correlations between $CO_2$ flux and soil moisture content or soil temperature were observed in none of the three soils ($r = 0.13$–$0.29$). Total $CO_2$ flux during the 3-year period (Table 3) was larger ($P < 0.05$) in the order ABg (11.6 ± 0.5 t C $ha^{-1}$), ABt (9.6 ± 0.5 t C $ha^{-1}$), and MPS (7.0 ± 0.1 t C $ha^{-1}$) soils.

The $CH_4$ flux ranged from −67 to 402 μg C $m^{-2}$ $h^{-1}$, −60 to 607 μg C $m^{-2}$ $h^{-1}$, and −20 to 653 μg C $m^{-2}$ $h^{-1}$, for the MPS, ABt, and ABg soils, respectively (Table 4). The average $CH_4$ flux, 91–218 μg C $m^{-2}$ $h^{-1}$, and total $CH_4$ flux during the 3-year period, 3.4–7.6 kg C $ha^{-1}$, were larger ($P < 0.05$) in the order ABg, ABt, and MPS soils. A positive correlation was observed between $CH_4$ flux and groundwater table in all the three soils ($r = 0.37$–$0.44$; $P < 0.05$).

### 3.3. Decomposition rate of SOC in soil mesocosms

The percentage of residual C at each period was obtained as the difference between the initial amounts of SOC and cumulative $CO_2$ fluxes, and plotted against the duration of incubation (Fig. 4). The C loss as $CH_4$ flux was not considered because it was much smaller than that as $CO_2$ flux. During the 3-year period of field incubation, 9.7% (MPS) to 17.6% (ABg) of SOC was lost. Similar values of 6.4% (MPS) to 17.2% (ABg) of SOC loss were estimated from the summes of total soil C remained in mesocosms (Table 5). The highly significant correlations between the % of C residual and incubation period ($r = 0.98$–$1.0$; $P < 0.005$) indicated that the rate of SOC decomposition did not decrease for 3 years. Determination constants were also high when their relationships were regressed to an exponential decay model, 0.97–0.99 (Fig. 4). Based on the regression to the exponential decal model, the rate constant of SOC decomposition for the MPS, ABt, and ABg soils was estimated 0.033 $y^{-1}$, 0.048 $y^{-1}$, and 0.066 $y^{-1}$, respectively.

**Table 3**
Carbon (C) composition of tropical peat soil samples.

| Soil sample | % Alkyl C (0–45 ppm) | % *O*-alkyl C (45–110 ppm) | % Aromatic C (110–160 ppm) | % Carboxyl C (160–190 ppm) | % Ketone C (190–220 ppm) |
|---|---|---|---|---|---|
| MPS | 32.9 | 26.4 | 26.9 | 12.5 | 1.3 |
| ABt | 27.3 | 31.5 | 27.1 | 12.6 | 1.5 |
| ABg | 21.3 | 36.5 | 32.5 | 8.8 | 0.9 |

## 4. Discussion

In the soil mesocosm experiments, soil samples collected from different forests with different vegetation types or similar plant species with different growth characteristics attributable to different nutritional and water conditions were incubated under same environmental conditions in oil palm plantation. Weeds did not grow in the mesocosms and the distribution of oil palm roots below the mesocosms may be poor based on the observation in another plantation (Lim et al., 2012) and non-adoptability of oil palm roots to anaerobic soil. Thus, the difference in $CO_2$ flux reflects the difference in the stability of SOM under oil palm cultivation. A possible cause of the variation in the stability of SOM is the differences in environmental conditions between the soil sampling sites, which are also determination factors of forest type (Page et al., 1999). The $CO_2$ fluxes from the ABt and ABg soils were correlated to groundwater table with the highest flux recorded by the ABg soil (625 mg C $m^{-2}$ $h^{-1}$) when the groundwater table was the lowest (−99 cm; Fig. 3). In temperate peatland, it has frequently been observed that a lower groundwater level resulted in a higher $CO_2$ flux (Moore and Dalva, 1993; Dinsmore et al., 2009; Berglund and Berglund, 2011). Similar trend has also been reported to tropical peatland (Melling et al., 2005a, 2013). Groundwater table in the Maludam National Park is generally higher than that in the oil palm plantation, but not even among the three forests. The difference in the groundwater level between the initial location and experimental plot was greater in the order ABg, ABt, and MPS samples (Table 1), which

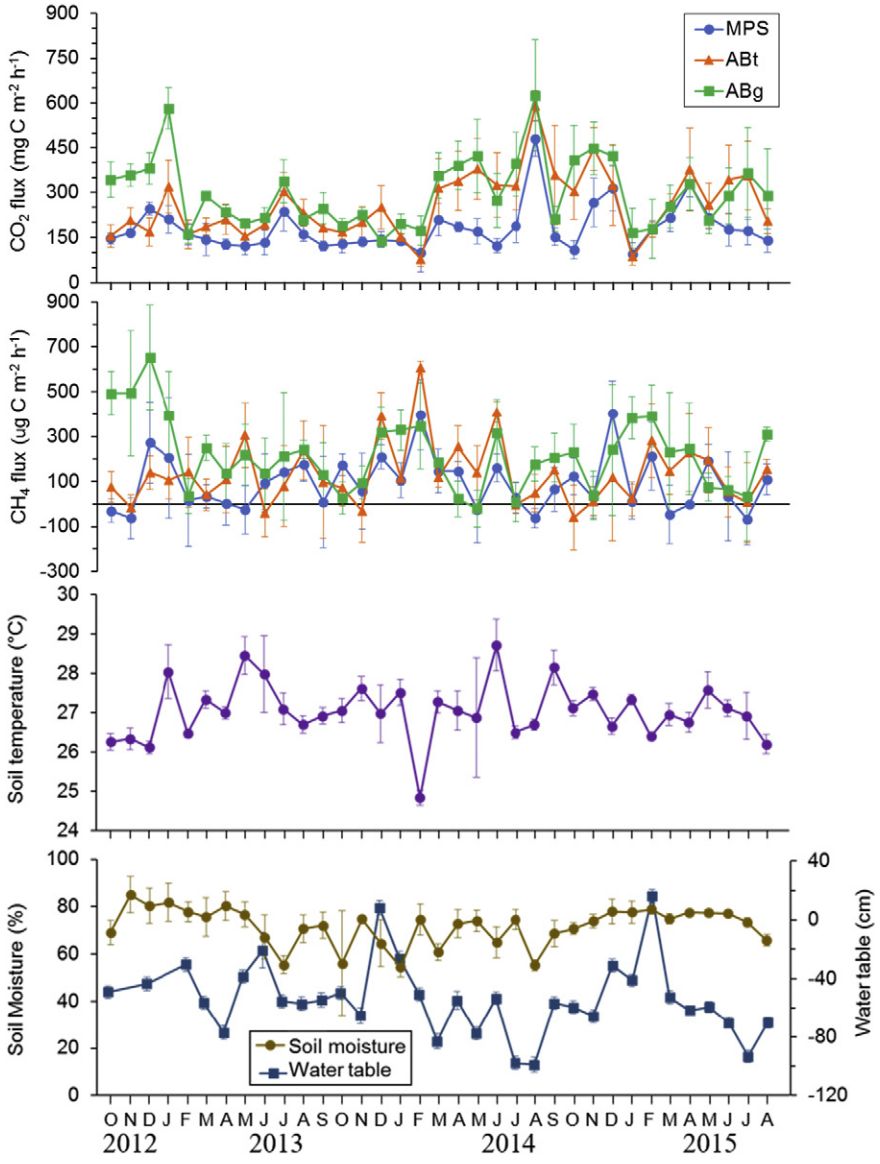


**Fig. 3.** Seasonal variations in $CO_2$ and $CH_4$ fluxes from tropical peat soils from three forest types and environmental variables in soil mesocosm experiment.

**Table 4**
Range, mean, and total of $CO_2$ and $CH_4$ fluxes from tropical forest peat soils installed in oil palm plantation during 3-year period (October 2012 – August 2015).

| Soil sample | $CO_2$ flux (mg C $m^{-2}$ $h^{-1}$) | $CH_4$ flux (μg C $m^{-2}$ $h^{-1}$) | Total $CO_2$ flux during 3-year period (t C $ha^{-1}$) | Total $CH_4$ flux during 3-year period (kg C $ha^{-1}$) |
|---|---|---|---|---|
| MPS | 95–480 (181 ± 38[a]) | −67–402(91 ± 108) | 7.0 ± 0.1 c[‡] | 3.4 ± 0.3 c |
| ABt | 78–592 (260 ± 66) | −60–607 (134 ± 109) | 9.6 ± 0.5 b | 5.0 ± 0.3 b |
| ABg | 138–625 (300 ± 68) | −20–653 (218 ± 130) | 11.6 ± 0.5 a | 7.6 ± 0.4 a |

[a] Average ± standard error.
[‡] Values followed by different letter differ at $P < 0.05$.

may contribute to the higher $CO_2$ fluxes from the ABg and ABt soils than that from the MPS soil.

Another possible cause of the variation in the rate of SOM decomposition is the variation in the structural property of SOM, since the larger total $CO_2$ flux was recorded by the soil sample having a larger % *O*-alkyl C (Table 3). Krosshavn et al. (1992) showed a decrease in % *O*-alkyl C and an increase in % alkyl C in peat bogs with increasing degree of decay or after 1-year incubation. Leifeld et al. (2012) also reported that % *O*-alkyl C was the best proxy for respiration rate in a disturbed temperate peatland, despite many other measured physico-chemical variables. Using Indonesian and Malaysian peat soils, Purwanto et al. (2005) showed a negative correlation between the rate constant of N mineralization and the ratio of % alkyl C to % *O*-alkyl C. The ratio of % carbohydrate C to % alkyl C and carbohydrate C content were also correlated positively to $CO_2$ and $CH_4$ production rates in a neotropical peatland (Wright et al., 2011). As such, it is considered that the relative abundance of *O*-alkyl C, which is derived mainly from polysaccharides such as cellulose and hemicellulose, is a major determination factor of the rate of SOM decomposition in tropical peat soils after reclamation. Krosshavn et al. (1992) attributed the variation in the C composition estimated from $^{13}C$ CPMAS NMR spectra between peat bogs and a lawn fen to the difference in dominant plant species. In Wright et al. (2011), different $CO_2$ and $CH_4$ production rates from the peat soil with different C composition were associated with different vegetation. However, the difference in groundwater level also affects the quality of SOM from similar vegetation as is the case for the ABt and ABg soils. The smaller % aromatic C and the higher % carboxyl C as well as the smaller intensity of $CH_3O$ and aromatic C-O signals can be interpreted as the advances in oxidation and lignin degradation in the MPS and ABt soils than in the ABg soil. Further study is required to confirm the difference in the chemical composition of tissue components in tree plants representative for each forest.

The annual SOM decomposition rate had increased from 3.0% to 3.2% (MPS), 4.3% to 4.7% (ABt), and 5.6% to 6.4% (ABg) during the 3-year period. This may be related to the change in groundwater level, because the average groundwater table had decreased from −47.6 cm (first year) to −58.7 (second year) or −53.8 (third year) cm. According to Melling et al. (2013), $CO_2$ flux from microbial respiration in a peat soil did not change with growth of oil palms. Similar trend was also observed in peat soil at >3.5 m apart from the nearest oil palm (Dariah et al., 2014). Since their results show that there was no reduction in the SOM decomposition rate under the present groundwater management in the oil palm plantation, the difference in the residual SOM amount among the three forest soils might be enhanced with time.

The $CH_4$ fluxes in the present study (Table 4) were within the range observed in tropical peat swamp forest and palm plantations, −177 to

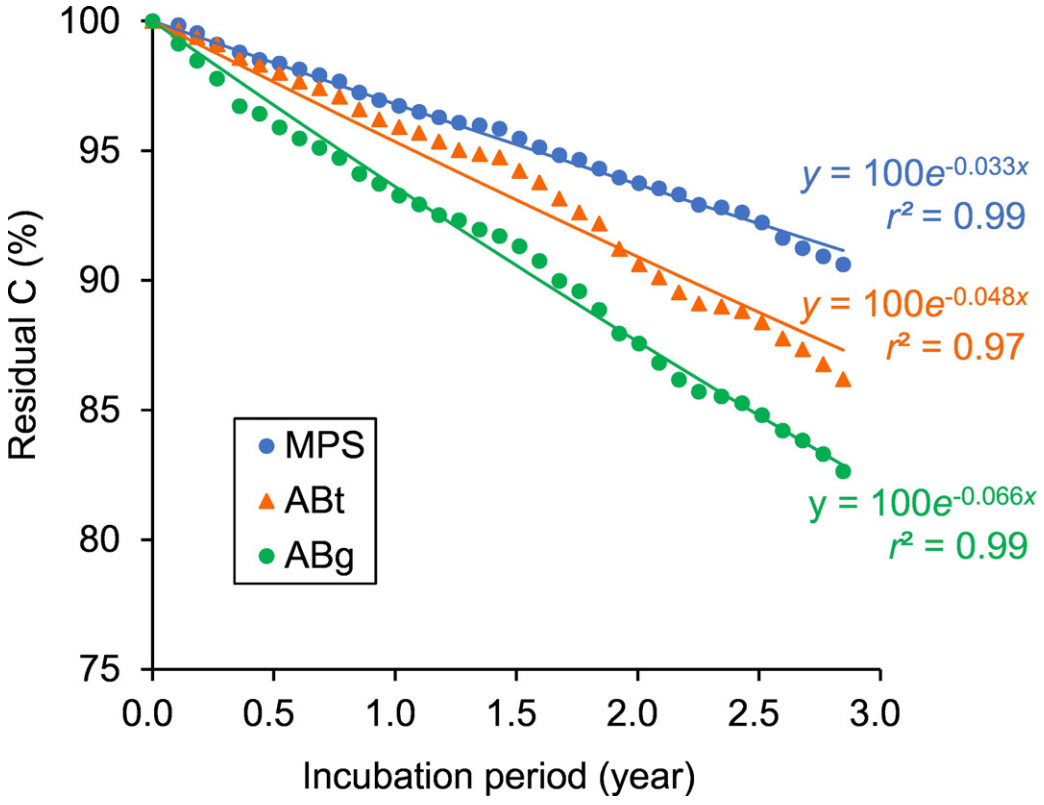


**Fig. 4.** Changes in the percentage of residual C in tropical peat soils from three forest types in soil mesocosm experiment.

**Table 5**
Total C loss of tropical forest peat soils installed in oil palm plantation during 3-year incubation.

| Soil sample | Based on $CO_2$ flux (%) | Based on soil C analysis (%) |
|---|---|---|
| MPS | 9.7 c[†] | 6.4 b |
| ABt | 14.0 b | 14.6 ab |
| ABt | 17.6 a | 17.2 a |

[†] Values followed by different letter differ at $P < 0.05$.

1460 μg C $m^{-2}$ $h^{-1}$ (Hadi et al., 2000; Melling et al., 2005b; Jauhiainen et al., 2008, 2014; Watanabe et al., 2008; Adji et al., 2014). Although the $CH_4$ flux correlated to groundwater table, their relationship was not so tight as was shown in small $r$ values (0.37–0.44) and reported for other tropical peat soils used for agriculture (Furukawa et al., 2005; Jauhiainen et al., 2014). According to Watanabe et al. (2009), $CH_4$ flux from a sago palm soil in an Indonesian peatland decreased exponentially from 500 to 1000 μg C $m^{-2}$ $h^{-1}$ to ≤50 μg C $m^{-2}$ $h^{-1}$ (including negative values) along with the decrease in groundwater table from >−15 cm to −45 cm or below. Compared to their data, groundwater table in the oil palm plantation was low as a whole, whereas the seasonal variation in soil moisture content did not follow the variation in groundwater table. The influence of groundwater level on $CH_4$ flux was indistinct probably due to these situations. Although the seasonal variations in $CH_4$ fluxes generally showed an opposite pattern to those in $CO_2$ fluxes, total $CH_4$ flux from the three Maludam soils was higher in the same order as total $CO_2$ flux (Table 4). Thus, the decomposability of peat SOM, which is related to the rates of development of reducing conditions in soil micro sites and supply of substrates for methanogens, was the major factor that determines $CH_4$ flux in the oil palm plantation. If the rates of $CH_4$ production in soils below 80 cm depth also differ from each other when the three forests are drained for oil palm cultivation, the differences in $CH_4$ flux among the three soils might be expanded.

Our study shows the importance of land choice for agricultural use in tropical peatland in terms of the sustainability of peat soil. Forest type, which is associated with groundwater and soil nutrition levels, is a potential criterion. Water management and land compaction prior to planting may also be important factors that affect the rate of peat decomposition (Lim et al., 2012; Melling et al., 2005a). Since we did not take the effect of soil compaction into consideration in this soil mesocosm experiment, it should be confirmed in another study.

## 5. Conclusions

The present study showed the variation in the sensitivity of SOM in tropical peat soils developed in different types of forest to land use change. The $CO_2$ and $CH_4$ fluxes after the soils were installed in oil palm plantation were in the order ABg > ABt > MPS. An annual SOC loss was estimated to be 3–6%. These variations could be attributed to the variation in SOC composition, in particular the relative abundance of *O*-alkyl C derived mainly from polysaccharides. Further research is required to differentiate the effect of vegetation (and growing conditions) and environmental conditions (especially water conditions) on the chemical structure and decomposability of peat SOM in different forest types.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.02.165.

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