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

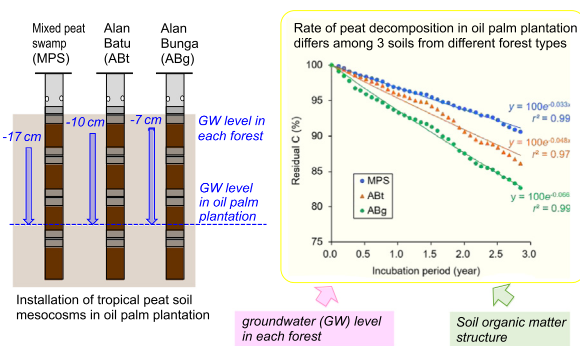
Faustina E. Sangok [a,b,*], Nagamitsu Maie [c], Lulie Melling [b], Akira Watanabe [a]

[a] Graduate School of Bioagricultural Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
[b] Sarawak Tropical Peat Research Institute, Lot 6035, Kota Samarahan Expressway, 94300 Kota Samarahan, Sarawak, Malaysia
[c] School of Veterinary Medicine, Kitasato University, Towada, Aomori 034-8628, Japan

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.

* Corresponding author at: Graduate School of Bioagricultural Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan.
E-mail address: fausties@sarawak.gov.my (F.E. Sangok).

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1. Introduction

Globally, tropical peatland area is estimated to be 4.41 × 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 × 10^4 km^2 (Mutalib et al., 1992), with 1.7 × 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.