

## Article

## Influence of Temperature and Water Conditions on the Mineralization Rate of Tropical Peat

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### Abstract

Tropical peat is woody peat that differs from sedge and moss peat found in temperate-boreal regions. As such, its decomposition characteristics are considered to be different. Here several factors that could influence mineralization rates of tropical peat were investigated, including forest type (mixed peat swamp (MPS) and Alan Bunga (ABg)), temperature (25°C and 35°C), and water content (60%, 80%, and 98%), in laboratory incubation experiments. Peat soil samples were incubated for one year with periodical gas sampling to measure CO<sub>2</sub> production. Cumulative amounts of CO<sub>2</sub> (ΣCO<sub>2</sub>) produced from MPS and ABg soils during the one year period were 0.6–3.2% of peat C and 2.4–8.1%, respectively, showing that ABg soil decomposed 2.5–5.3 times faster than MPS soil when incubated at identical conditions. Q<sub>10</sub> values ranged from 0.85 to 2.4. Water content bidirectionally influenced the decomposition rate of peat.

**Keywords:** Mineralization rate, oxygen, peat quality, temperature, tropical peat, water content.

### Introduction

Peatland accumulates 450–550 Pg of carbon (C) as humus, which is equivalent to 70% of atmospheric C stock (Parish et al., 2008). Peatland can be a significant C source when the environment changes through land-use change and global warming (Laiho, 2006). Therefore, many studies have focused on studying the influence of environmental changes on the decomposition rate of peat and the controlling factors in boreal climates (Silvola et al., 1996; Laiho, 2006 and references therein). However, while tropical peatland is estimated to accumulate 88.6 Pg C, accounting for 15–19% of global peat C pool (Page et al., 2011), comparatively few studies have been conducted on the same topic in these environments (e.g., Murayama and Baker, 1996; Hoyos-Santillan et al., 2016).

Tropical peat accumulates under tropical peat

swamp forests (TPSFs) and is woody peat that contains trunks, branches, and coarse roots in dark brown amorphous organic material. Several forest types dominate in a tropical peat dome, which generally shifts with the distance from a riverbank in a concentric fashion (Melling, 2016). In Sarawak, Malaysia, mixed peat swamp (MPS) dominates at riverbanks, which shifts into Alan Batu (ABt) and then Alan Bunga (ABg) forests toward the interior. The groundwater level and nutrient status of tropical peatlands also change with the distance from a riverbank. As such, physicochemical characteristics of different peats are different among forest types (Melling, 2016; Sangok et al., 2017).

Since the 1960s, countries in Southeast Asia, such as Indonesia and Malaysia, have turned tropical peatlands into oil palm plantations due to limited acreage of arable dry field. On reclamation of TPSF to oil palm plantations, original vegetation is clear-

cut, and the groundwater table is lowered to ca. 70 cm below the surface. In such situations, concerns arise that these environment changes may accelerate the decomposition of peat. To help investigate this and to contribute to better management of oil palm plantations, it is important to better understand the decomposition rate of peat and the influencing factors of decomposition in these environments.

Sangkok et al. (2017) conducted a decomposition incubation experiment in which mesocosm columns, packed with freshly collected peat samples from native tropical swamp forests, were incubated at an oil palm plantation for three years. The quality of tropical peat was found to be the crucial factor that influenced the mineralization rate of peat in that study. However, it was not clear how temperature and water conditions, which are important factors that influence microbial activity, affected the mineralization rates. In the study described herein, the influence of temperature and water conditions on the rate of tropical peat mineralization was investigated. Two different peat samples, MPS and Alan Bunga (ABg), were incubated under controlled temperatures (25°C and 35°C) and water content (60%, 80%, 98%) for one year, and the cumulative amount of CO<sub>2</sub> (ΣCO<sub>2</sub>) produced was compared between treatments.

## Materials and Methods

### Peat samples

Peat soil samples were collected at Maludam National Park, the largest preserve of native tropical swamp forests in Sarawak, Malaysia. The vegetation zone shifts along with the distance from riverbanks, as is often observed for tropical peat swamps: MPS is formed along neighboring riverbanks, and ABg is formed more interior. Vegetation associated with MPS is mainly composed of *Gonystylus bancanus*, *Dactylocladus stenostachys*, *Copaiifera palustris*, and four *Shorea spp.*, while that of ABg is dominated by *Shorea albida* (Melling et al., 2016). Subsurface peat samples (20–40 cm below the surface) were collected in a MPS forest (1°25'N, 111°07'E) and an ABg forest (1°27'N, 111°09'E). Peat soil samples used were identical to those used in Sangkok et al. (2017), and their chemical properties, as reported in Sangkok et al. (2017), are listed in Table 1. Alkyl C/O-alkyl C ratio of MPS peat were higher than that of ABg peat, suggesting that the former is more microbially

decomposed than the latter (Baldock et al., 1997).

### Incubation experiment

Peat soil samples were dried at room temperature to a moisture level of 50–60% prior to passing samples through a 2-mm mesh sieve. Peat soil samples amounting to 1 g dry weight were placed into 100-mL Erlenmeyer flasks. Flasks were capped tightly with double-layer butyl rubber plugs and incubated for one year at 25°C or 35°C in temperature-controlled incubators. Water content was regulated at 60%, 80%, and 98% on a wet soil weight basis for each temperature. The 98% moisture treatment was prepared by adding 50 mL of ultrapure water (i.e., submerged conditions). Each treatment was prepared in four replicates. Notation of samples of different treatments were done by connecting treatment conditions with a hyphen (e.g., MPS-60%25°C denotes the MPS soil incubated at a water content of 60% at 25°C). During the incubation period, a 4-mL portion of gas inside the flask was collected once a week (until 84 days) or once a month (after 84 days) using a 10-mL air-tight syringe and transferred into a 4-mL pre-evacuated glass vial (Nichiden-Rika Glass Co., Tokyo, Japan) to determine the amount of CO<sub>2</sub> produced in the treatments. After each gas sampling, the gas in the flasks was replaced by CO<sub>2</sub>-free air (N<sub>2</sub>:79%, O<sub>2</sub>:21%), and ultrapure water was added to maintain the setting value within 1% error.

### GC analysis

Concentrations of CO<sub>2</sub> in the gas samples were

**Table 1** Chemical properties of peat samples<sup>1)</sup>

|   | MPS  | ABg  |
|---|------|------|
| pH (H <sub>2</sub> O)                                 | 3.6  | 3.6  |
| Loss on ignition (%)                                  | 98   | 99   |
| Total C (g kg <sup>-1</sup> )                         | 535  | 520  |
| Total N (g kg <sup>-1</sup> )                         | 20   | 13   |
| C/N   | 27   | 40   |
| Carbon composition based on <sup>13</sup> C CPMAS NMR |      |      |
| %Alkyl C (0–45ppm)                                    | 32.9 | 21.3 |
| %O-alkyl C (45–110ppm)                                | 26.4 | 36.5 |
| %Aromatic C (110–160ppm)                              | 26.9 | 32.5 |
| %Carboxyl C (160–190ppm)                              | 12.5 | 8.8  |
| %Ketone C (190–220ppm)                                | 1.3  | 0.9  |
| Alkyl C/O-alkyl C                                     | 1.25 | 0.58 |

<sup>1)</sup> Sangkok et al. (2017)

measured by introducing a 100-mL aliquot into a gas chromatograph (Shimadzu GC-2010 Plus, Kyoto, Japan) equipped with a barrier ionization discharge detector.

### Statistics

Cumulative  $\text{CO}_2$  amounts were compared statistically among the treatments using the Tukey-Kramer test (JMP ver. 9.0.3, SAS Institute Inc., NC, USA).

## Results

### Periodical changes of $\text{CO}_2$ production rate

Periodical changes in the cumulative  $\text{CO}_2$  production are shown in Figure 1. The pattern of cumulative  $\text{CO}_2$  production followed an exponential rise to maximum relationship with time for the 60% and 80% water content treatments. In contrast, the cumulative  $\text{CO}_2$  production followed a sigmoid curve for the 98% water content. Given that the water content of MPS and ABg samples prior to their use in the experiments were 51% and 61%, respectively, microbes may have needed a lag phase for adaption to a new environment for the 98% water content treatments. Larger variances were observed between replicates for ABg-35°C, which could be due to micro-scale heterogeneity of dissolved oxygen and peat quality among replicates

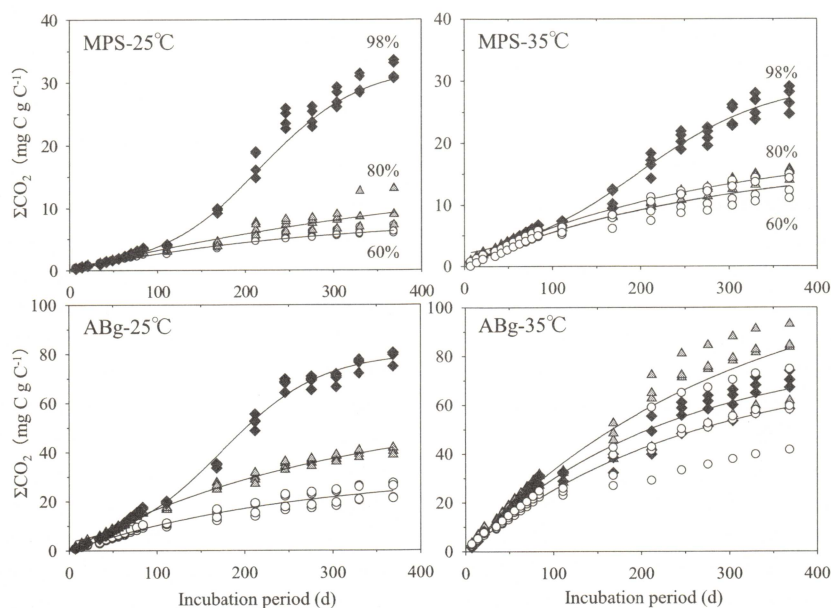
(Pedersen et al., 2015). Cumulative amounts of  $\text{CO}_2$  emitted during the one year period ( $\Sigma\text{CO}_2$ ) accounted for 0.6–3.2% and 1.3–2.7% of total peat C at 25°C and 35°C, respectively, for MPS soil (Table 2). These values for the ABg soil samples were 2.4–7.9% and 5.9–8.1% at 25°C and 35°C, respectively.

### Influence of temperature on $\Sigma\text{CO}_2$

The  $\Sigma\text{CO}_2$  of each treatment and the ratio of  $\Sigma\text{CO}_2$  between two treatments are shown in Table 2. The  $\Sigma\text{CO}_2$  increased as the temperature increased from 25°C to 35°C when the water content was 60% or 80%. The rate of the increase in  $\Sigma\text{CO}_2$  with increasing temperature by 10°C ( $Q_{10}$ ) was higher for the ABg soil than in the MPS soil and higher with lower water content, with a maximum observed value of 2.4 for the ABg-60% treatment. The  $\Sigma\text{CO}_2$  was lower for treatments incubated at 35°C compared to 25°C when incubated with a water content of 98%, leading to  $Q_{10}$  values less than one for both MPS and ABg soils (Table 2) This was likely due to the shift of the peat environment from aerobic to anaerobic conditions..

### Influence of forest type on $\Sigma\text{CO}_2$

The  $\Sigma\text{CO}_2$  of the ABg soil was 2.5–5.3 times greater than that of the MPS soil in identical treatment conditions (Table 2). The difference between the two soils was the largest when water content was 80%.



**Figure 1.** Periodical changes in cumulative  $\text{CO}_2$  production from peat soil samples incubated at different conditions. Water content: white circle, 60%; gray triangle, 80%; and black diamond, 98%.



**Table 2**  $\Sigma\text{CO}_2$  from each treatment and their ratios

| Treatment    | $\Sigma\text{CO}_2$<br>( $\text{mg C g}^{-1} \text{ C y}^{-1}$ ) | $\frac{35^\circ\text{C}}{25^\circ\text{C}}$<br>( $Q_{10}$ ) | $\frac{\text{ABg}}{\text{MPS}}$ | $\frac{80\% \text{ or } 98\%}{60\%}$ |
|--------------|--|---|---------------------------------|--------------------------------------|
| MPS-60%-25°C | 6.4±0.6 g <sup>1)</sup>  | –   | –                               |                                      |
| MPS-80%-25°C | 9.6±2.5 fg   | –   | –                               | 1.5±0.3                              |
| MPS-98%-25°C | 32±1 cd  | –   | –                               | 5.1±0.1                              |
| MPS-60%-35°C | 13±2 efg   | 2.1±0.2   | –                               |                                      |
| MPS-80%-35°C | 15±1 efg   | 1.6±0.3   | –                               | 1.2±0.1                              |
| MPS-98%-35°C | 27±2 cde   | 0.85±0.1  | –                               | 2.1±0.2                              |
| ABg-60%-25°C | 24±3 def   | –   | 3.8±0.2                         |                                      |
| ABg-80%-25°C | 41±1 c   | –   | 4.2±0.3                         | 1.7±0.1                              |
| ABg-98%-25°C | 79±3 a   | –   | 2.5±0.1                         | 3.3±0.1                              |
| ABg-60%-35°C | 58±14 b  | 2.4±0.3   | 4.5±0.3                         |                                      |
| ABg-80%-35°C | 81±13 a  | 2.0±0.2   | 5.3±0.2                         | 1.4±0.3                              |
| ABg-98%-35°C | 67±7 ab  | 0.86±0.1  | 2.5±0.1                         | 1.2±0.3                              |

<sup>1)</sup> Levels not connected with same alphabetical letter indicate significant differences ( $p < 0.05$ ).

### *Influence of water conditions on $\Sigma\text{CO}_2$*

When the MPS and ABg soils were incubated at 25°C,  $\Sigma\text{CO}_2$  increased by 5.1 and 3.3 times, respectively, as the water content increased from 60% to 98%, with the exception of the ABg-98%-35°C treatment (Table 2). The increasing rate of  $\Sigma\text{CO}_2$  with increasing water content from 60% to 98% was less at 35°C, by 2.1 and 1.4 times for MPS and ABg soils, respectively, with the exception of the ABg-98%-35°C treatment where there was no significant difference in  $\Sigma\text{CO}_2$  from the ABg-60%-35°C.

## **Discussion**

### *Influence of temperature and C type on the rate of peat mineralization*

According to Sangok et al. (2017), the annual rate of peat decomposition in a three-year field incubation experiment at an oil palm plantation was 3.2% for MPS soil and 6.4% for ABg soil, where the soil temperatures (at a depth of 5 cm) ranged from 23 to 33°C. Observed peat mineralization rates were intermediate in this study, suggesting that the results reflect variation in peat decomposition rates in the field. With respect to the influence of temperature,  $Q_{10}$  values in this study ranged from 1.6 to 2.4, with the exception of the 98% water content treatment, were similar to those reported for peats and soils in various regions (2.4: Lloyd and Taylor, 1994; 2.4 with a range

of 1.3–3.3: Raich and Schlesinger, 1992). Variations in  $Q_{10}$  values can occur due to differences in the C quality and temperature ranges (Inglett et al., 2012). Clein and Schimel (1995) reported  $Q_{10}$  values up to 23.4 in boreal regions. As such, increases in the soil temperature increases  $\text{CO}_2$  production rate at a higher rate for boreal peatlands than tropical peatlands. It is important to note that soil environments, in terms of  $\text{O}_2$  conditions, can change as temperature increases, which can lead to adverse effects on soil microbial activity (see below).

Peat quality is often ascribed to the most significant factor that influences mineralization rate or more accurately, the mineralizable C pool (Hogg et al., 1992; Laiho, 2006; Grover and Baldock, 2012). In our experiment, the rate of mineralization of ABg soil was 2.5–5.3 times faster than that of MPS soil. According to Bridgham and Richardson (1992), peats that have previously been exposed to long periods of aerobic decomposition may be more resistant to further decomposition. The groundwater table of the ABg forest (from –6.9 to –7.6 cm) was higher than that of the MPS forest (from –13.3 to –20.7 cm) (Sangok et al., 2017), and the alkyl C/O-alkyl C ratio of the ABg soil sample was lower than that of the MPS soil (Table 1). Therefore, the ABg soil is likely to have undergone less microbial decomposition (Baldock et al., 1997; Grover and Baldock, 2012) and contained a larger amount of readily oxidizable C under aerobic conditions. Data confirm that the chemical

characteristics of soil are major influencing factors that control decomposition rates of tropical peat.

### *Bidirectional influence of water content on the rate of peat mineralization*

In peatlands with a certain level of microbial activity and stagnant water, transfer of molecular oxygen ( $O_2$ ) is limited by low  $O_2$  diffusion coefficients and  $O_2$  consumption in upper layers. Under anaerobic conditions, decomposition of submerged peat is restricted due to prevention of phenol oxidase from eliminating phenolic compounds that inhibit biodegradation (Pind et al., 1994; Freeman et al., 2001). However, in our experiment, air inside the flask was regularly replaced with  $CO_2$ -free air ( $N_2$ : 78%;  $O_2$ : 22%), and as such,  $O_2$  may not have been consumed to levels that would constrain the mineralization of peat at 25°C. Under such aerobic conditions, water promotes transportation/diffusion of substrates/enzymes and mobility of microbes, resulting in higher decomposition rates at a higher water content (Stark and Firestone, 1995; Waddington et al., 2001). The response of mineralization rates to changes in water content varies depending on peat quality (Husen et al., 2014). At higher temperatures (i.e., 35°C),  $\Sigma CO_2$  was lower in the 90%-35°C treatment than in the 80%-35°C treatment (Fig. 1; Table 2), likely due to exhaustion of dissolved  $O_2$  because (1) the saturated-dissolved  $O_2$  is less at a higher temperature (8.11 mg  $O_2$   $L^{-1}$  at 25°C vs. 7.04 mg  $O_2$   $L^{-1}$  at 35°C), (2) the  $O_2$  diffusion coefficient is smaller at a higher water

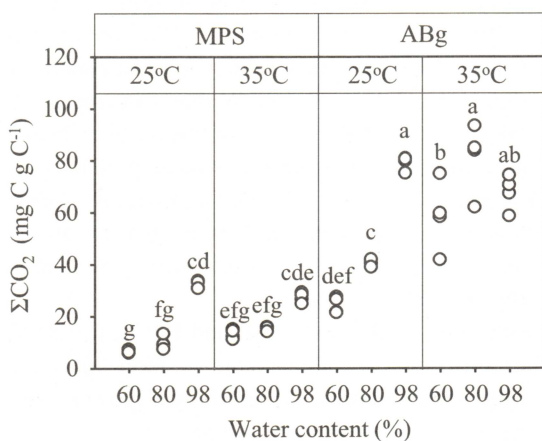
content ( $1.98 \times 10^{-5}$   $m^2$   $s^{-1}$  in air vs.  $1.9 \times 10^{-9}$   $m^2$   $s^{-1}$  in water; Hillel, 1998), and (3) microbial activity (i.e., soil respiration) is greater at a higher temperature under aerobic conditions (Pietikäinen et al., 2005). This interpretation is in agreement with a conceptual model proposed by Skopp et al. (1990), in which microbial activity was defined as a function of soil water content that controls substrate diffusion rate and  $O_2$  diffusion rate. In their model, a higher water content brings a higher substrate diffusion rate and a lower  $O_2$  diffusion rate. Until optimum water content for  $CO_2$  production is reached, the rate of peat decomposition increases as the water content increases. A good example of this can be observed in a depth profile of decomposition rates in peat: a secondary or even primary decomposition peak can exist at the range of the water level variation in the hammock of boreal peat (Laiho, 2006). Therefore, water content is considered to have a bidirectional effect on the rate of decomposition of tropical peat as is the case with temperate-boreal peat, while the saturated-dissolved  $O_2$ , and as such the optimum water content for  $CO_2$  production, is probably lower for tropical peat compared with temperate-boreal peat.

### *Implications*

In an oil palm plantation,  $CO_2$  flux from soil has been considered to be strongly controlled by water-filled pore space (Melling et al., 2005). Peat compaction, which is a common practice when reclaiming tropical wetland to oil palm plantations in Malaysia, increases bulk density, lowers porosity of surface layers, and thus increases water-holding capacity of soil (Melling and Henson, 2011). Thus, soil compaction may decelerate the rate of peat decomposition in deep layers by increasing water content and lowering diffusion of  $O_2$ . Future research is needed to elucidate changes in the soil environment caused by soil compaction to better understand their contribution to sustainable management of tropical peatlands in terms of peat decomposition and  $CO_2$  emission.

### *Conclusion*

We confirmed that differences in the chemical properties of peat and water content greatly influenced the rate of mineralization of tropical peat, as is the case with temperate-boreal peat. Effects of temperature on the rate of mineralization of tropical peat ( $Q_{10} = 1.6$ – $2.4$ ; aerobic conditions) were also similar with those



**Figure 2.** Comparison of cumulative  $CO_2$  production between treatments. Different letters on plots indicate the presence of statistically significant differences between treatments ( $p < 0.05$ ).



observed in other regions. Since water content exerts bidirectional influence on the rate of decomposition of tropical peat, the influence of water content on the decomposition rate of peat needs to be carefully examined in future studies.

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