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Soil carbon dioxide emissions due to oxidative peat decomposition in an oil palm plantation on tropical peat

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ABSTRACT

Soil carbon dioxide (CO_2) efflux was measured continuously for two years using an automated chamber system in an oil palm plantation on tropical peat. This study investigated the factors controlling the CO_2 efflux and quantified the annual cumulative CO_2 emissions through soil respiration and heterotrophic respiration, which is equivalent to oxidative peat decomposition. Soil respiration was measured in close-to-tree (< 2.5 m, CT) and far-from-tree (> 3 m, FT) plots, and heterotrophic respiration was measured in root-cut (RC) plots by a trenching method. The daily mean CO_2 efflux values (mean ± 1 standard deviation) were 2.80 ± 2.18, 1.59 ± 1.18, and 1.94 ± 1.58 $\mu mol\ m^{-2}\ s^{-1}$ in the CT, FT, and RC plots, respectively. Daily mean CO_2 efflux increased exponentially as the groundwater level or water-filled pore space decreased, indicating that oxidative peat decomposition and gas diffusion in the soil increased due to enhanced aeration resulting from lower groundwater levels. Mean annual gap-filled CO_2 emissions were 1.03 ± 0.53, 0.59 ± 0.26, and 0.69 ± 0.21 $kg\ C\ m^{-2}\ yr^{-1}$ in the CT, FT, and RC plots, respectively. Soil CO_2 emissions were significantly higher in the CT plots ($P < 0.05$), but did not differ significantly between the FT and RC plots. This implies that root respiration was negligible in the FT plots. Heterotrophic respiration accounted for 66% of soil respiration. Annual CO_2 emissions through both soil and heterotrophic respiration were smaller than those of other oil palm plantations on tropical peat, possibly due to the higher groundwater levels, land compaction, and continuous measurement of soil CO_2 efflux in this study. Mean annual total subsidence was 1.55 to 1.62 $cm\ yr^{-1}$, of which oxidative peat decomposition accounted for 72 to 74%. In conclusion, water management to raise groundwater levels would mitigate soil CO_2 emissions from oil palm plantations on tropical peatland.

1. Introduction

Peatland stocks approximately one-third of the global terrestrial carbon (C) in 3% of the global terrestrial area (Maltby and Immirzi, 1993), and approximately 25 Mha are in Southeast Asia, especially in Indonesia and Malaysia (Page et al., 2011). However, tropical peatland has been rapidly reclaimed since the 1990s, mainly for oil palm and *Acacia* plantations. By 2015, oil palm plantations had expanded to cover an area of 4.3 Mha on peat in Indonesia and Malaysia (Miettinen et al., 2016). Because the agricultural use of tropical peatland is commonly accompanied by drainage, the aerobic mineralization of peat soil is promoted, resulting in large carbon dioxide (CO_2) emissions (e.g., Furukawa et al., 2005; Couwenberg et al., 2010; Hooijer et al., 2012). Peat is usually compacted using heavy machinery before planting in Malaysia to enhance its bearing capacity for trees and to increase soil moisture via capillary water rise (Dislich et al., 2016). This compaction practice is expected to depress peat oxidative decomposition due to the increase in soil water content and decrease in soil gas diffusivity (Melling et al., 2005, 2013a).

It has been reported that CO_2 emissions from tropical drained peatland are an important part of the global C cycle (Sjögersten et al., 2014; Miettinen et al., 2017), and therefore it is important to quantify oxidative peat decomposition or heterotrophic respiration (R_H) from total soil respiration (R_S) separately. However, there have been few

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studies of R_H in tropical peatland, despite R_H being an important component of R_S that corresponds to oxidative peat decomposition. For oil palm plantations on peat, some studies have measured R_H periodically at intervals of one or more months for periods equal to or less than 1 year (Melling et al., 2005, 2013a, 2013b; Dariah et al., 2014; Husnain et al., 2014; Marwanto and Agus, 2014; Sakata et al., 2015; Comeau et al., 2016). Due to the limitations of field studies, the controlling factors of soil CO_2 efflux are not well understood at the process level. For example, it was reported that no significant relationship exists between R_S and groundwater level (GWL) (Jauhiainen et al., 2008), probably due to the disconnection of capillary force under dry conditions, resulting in soil moisture in the topsoil becoming decoupled from the GWL (Ishikura et al., 2017). Soil moisture in the topsoil can be a better predictor than GWL for soil CO_2 efflux (Melling et al., 2005, 2013a), because soil moisture is affected more by capillary rise than GWL when a peat soil is compacted (Price, 1997; Michel et al., 2001). However, the relationship between soil CO_2 efflux and soil moisture in tropical peat ecosystems is still not well understood. For a better understanding, long-term continuous measurement of both R_S and R_H is necessary to capture diurnal variation, detect the response of soil CO_2 efflux to dynamic environmental variations, and reduce the uncertainties in assessment of annual CO_2 emissions. To our knowledge, no studies have measured R_S and R_H continuously in an oil palm plantation on peat.

Oxidative peat decomposition induces subsidence together with physical consolidation and shrinkage (Stephens and Stewart, 1976; Wösten et al., 1997; Hooijer et al., 2012). If the contribution of peat oxidation to total subsidence is determined, CO_2 emissions through peat decomposition can be estimated from subsidence monitoring (Couwenberg and Hooijer, 2013). However, the extent of this contribution has not yet been determined, because it depends on peat conditions, such as GWL and the time since drainage. Field studies involving simultaneous measurement of peat subsidence and oxidative peat decomposition could enable this to be determined, but only a few studies have been reported (Wakhid et al., 2017).

Therefore, R_S and R_H due to oxidative peat decomposition were measured continuously for two years using an automated chamber system, together with GWL, soil moisture, and peat subsidence in an oil palm plantation established on tropical peat. The objectives of this study were to investigate seasonal changes in R_S and R_H in relation to soil water conditions, quantify annual cumulative R_S and R_H values, and evaluate the contribution of oxidative peat decomposition to subsidence.

2. Material and methods

2.1. Site description

This study was conducted in an oil palm (*Elaeis guineensis* Jacq.) plantation (2°11′N, 111°50′E) in a watershed of the Rajang River in Sibu, Sarawak, Malaysia (Fig. 1) at an elevation of approximately 25 m above sea level. The mean annual air temperature and precipitation between 2004 and 2016 were 26.5 ± 0.2 °C and 2915 ± 213 mm yr^{-1} (mean ± 1 standard deviation (SD)), respectively, at the Sungai Salim B meteorological station (Department of Irrigation and Drainage Malaysia), which is 7.4 km from the study site. In September 2004, a mixed peat swamp forest on an ombrotrophic peat dome was converted to an oil palm plantation, with the installation of ditches and water gates; artificial compaction to prevent palms from leaning and toppling was performed during land preparation. The soil type was a Sapric Histosol (IUSS Working Group WRB, 2015), with a peat depth of 12.7 m. Palm seedlings were planted on a triangular grid spacing of 8.5 m between trees (153 trees ha^{-1}; Fig. 2), and the ground was sparsely covered by fern plants (*Stenochlaena palustris* (Burm. f.) Bedd.). The lower fronds of oil palm trees were periodically lopped and piled in inter-row spaces. Thus, little leaf litter accumulated on the ground, except for some areas with fern plants. In 2014, the palm trees were 9 years old, and the canopy height was about 8 m. Oil palm plantations are commonly replanted every 25–30 years (Basiron, 2007), so the study site was in the first cycle of cultivation. The following fertilizers were applied together four times a year (January, March, July–August, and September–October) within 1 m of each stem: 74–147 kg N ha^{-1} yr^{-1} of urea, 7–9 kg P ha^{-1} yr^{-1} of rock phosphate, and 239–311 kg K ha^{-1} yr^{-1} of muriate of potash (KCl). Copper, zinc, and boron were applied as micronutrients at 8–16 kg ha^{-1} yr^{-1} in May–June every year, and kieserite ($MgSO_4{\cdot}H_2O$) was also applied at rates of 80 kg ha^{-1} in October 2014, 119 kg ha^{-1} in May 2015, and 80 kg ha^{-1} in January 2016, respectively.

2.2. Experimental design and chamber measurement

In April 2014, an experimental area without fern plants was established, and the following treatments were applied (Fig. 2):

Close-to-tree (CT, four plots): distance from the nearest tree < 2.5 m, corresponding to R_S.

Far-from-tree (FT, four plots): distance from the nearest tree > 3 m, corresponding to R_S.

Root-cut (RC, four plots): distance from the nearest tree > 3 m with trenching, corresponding to R_H.

In each RC plot, four stainless steel plates were inserted surrounding an area of 40 × 80 cm^2. The depth of insertion was 80 cm, which was almost equivalent to the lowest GWL. In May 2014, 1 month later, an automated chamber system was installed in the experimental area. The system consisted of 16 chambers, an infrared CO_2 analyzer (LI-820, LI-COR, Inc., Lincoln, Nebraska, USA), a programmable data logger (CR1000, Campbell Scientific Inc., Logan, Utah, USA), and an air pump and solenoid valves (Hirano et al., 2009). The chamber consisted of an opaque polyvinyl chloride (PVC) cylinder (height: 40 cm; inner diameter: 25 cm). Chambers were inserted 2–3 cm deep into the soil. One chamber was installed in each CT and FT plot, and two chambers were installed in each RC plot (Fig. 2).

An opaque PVC lid was attached to the chamber top that opened vertically and closed under the control of the data logger. Each chamber closed for 225 s in sequence, one after the other, and it took 1 h for all chambers to close/open in rotation. The air in the headspace of each chamber was circulated through the CO_2 analyzer when the chambers were closed. The CO_2 concentration was measured at 10-s intervals and recorded in the data logger. In August 2015, a greenhouse gas analyzer (Ultraportable Greenhouse Gas Analyzer 915-0011, Los Gatos Research, Inc., San Jose, California, USA) was placed in the air circulation line to measure CO_2, methane, and water vapor concentrations. Although measurements began in May 2014, data for a two-year period from January 2015 were used, because additional CO_2 emissions resulting from the decomposition of dead roots left in the trenched plots were expected to occur for several months after trenching (Hanson et al., 2000; Comeau et al., 2016). One palm tree fell on a chamber in a CT plot in August 2015, and the chamber was then moved to an FT position. Thus, the number of CT plots decreased to three, while the number of FT plots increased to five in 2016. CO_2 data from the CO_2 analyzer were primarily used; data from the greenhouse gas analyzer were used as an alternative when the LI-820 malfunctioned. During the two years of 2015 and 2016, 23% of the data was lost, mainly due to power problems.

Soil CO_2 efflux was calculated from the increase in CO_2 concentration in the chamber headspace during the 90–220 s after the chamber closing:

$$F = \frac{PH}{RT_{\mathrm{air}}}\frac{dC}{dt} \tag{1}$$

where F is soil CO_2 efflux (μmol m^{-2} s^{-1}), P is air pressure (101.325 kPa), H is the aboveground height of a chamber, R is the gas constant (8.314 Pa m^3 K^{-1} mol^{-1}), T_{air} is air temperature (K), and $dC/$