Study on decomposition characteristics of peat soils under oil palm plantation in Riau and West Kalimantan, Indonesia

Setiari Marwanto

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Acknowledgment

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Chapter 1. Introduction

1.1. Background of Study

1.1.1. Peatlands in Indonesia

Peat is the accumulation of dead plant in a waterlogged condition which results in a very slow decomposition. The high water table prevents aerobic decomposition of dead plants and accumulates the topogenous peat. The continuous accumulation of peat forms ombrogenous peat, where the peat rises above the water table level and grows depending on the rainfall and internal nutrient cycle (Driessen, 1978). Indonesia had 14.9 Mha of peatland which spread out in three big islands of Sumatra (43 %), Kalimantan (32 %) and Papua (25 %) (Ritung et al. 2011).

Peatland in Indonesia had an important role in a global carbon (C) cycle. In natural conditions, peat grows with the accumulation rate of 0.15–10 mm yr^{-1} (Dommain et al., 2014; Page et al., 2004). It is confirmed that the Indonesian peatland began to act as C sinker since the late Pleistocene and Holocene. Peatland formation in Kalimantan and Sumatra started at 5,000–30,000 ^{14}C years Before Present (Hapsari et al., 2017; Biagioni et al., 2015; Hope et al., 2005; Page et al., 2004; Anshari et al., 2001; Supardi et al., 1993; Siefermann et al.,1988). According to the simple calculation using the C content and bulk density variables, Indonesian peatlands contain a huge pool of 57.4 Gt C, which equal to 9–12% of global peat C (Page et al., 2011).

Peatland has been regarded to be less favorable for crop production because of low nutrient content, low pH, low bulk density, low bearing capacity, and high water table level (Agus and Subikse, 2008; Haraguchi et al., 2000; Driessen, 1978). However, due to the limited productive land of mineral soils, peatlands are considered potential areas for agricultural crops including oil palm (*Elaeis guineensis* Jacq.) plantation.

The massive expansion of oil palm plantation on peatlands occurs in Kalimantan and Sumatra Islands which addresses the world’s demand for palm oil.

Palm oil is a primary source of vegetable oil, fats, and biodiesel in the world (Carter et al., 2007; Fargione et al., 2008; Zhou and Thomson, 2009), and its demand increases over the time. Recently, Indonesia had 12.3 Mha of total oil palm plantation area (Secretariat of Directorate General of Estate Crops, 2016), where approximately 1.7 Mha is located on peatlands (Gunarso et al., 2013).

The expansion of oil palm plantation in tropical peatlands contributes significantly to the national economic growth and the increase of rural household income of Indonesia (Sayer et al., 2012). However, this expansion in peatlands draws global concern because oil palm plantation always drains the water, which accelerates peat decomposition (Carlson et al., 2015; RSPO, 2012). The peat decomposition releases carbon dioxide (CO_2) and mineral nutrients which affects the lowering oil palm productivity and environmental degradation (Goh and Hardter, 2003; Driessen and Supraptohardjo, 1974; Hergoualc'h and Verchot, 2014; Melling et al., 2005). More efforts are needed for achieving better understanding on the dynamics of CO_2 emission and peat nutrients in order to develop appropriate management practices in oil palm plantation that could sustain oil palm productivity as well as the global environment.

1.1.2. Problems accompanied with oil palm plantation development in tropical peatlands

Natural peatland is the most effective pool to store organic matter in the terrestrial ecosystem of the world (Page et al., 2011). The severe degradation of organic matter occurred when natural peatland converted to oil palm plantation. Drainage in oil palm plantation exposes peat organic matter into an aerobic condition and usually accelerates decomposition (Carlson et al., 2015; Hooijer et al., 2010), which breaks down the organic substrate into CO_2 gas and mineral nutrients (Yule et al., 2016; Cussel et al., 2013; Bragazza et al., 2008; Adamson et al., 2001).

CO_2 emission during peat decomposition

Atmospheric CO_2 is the main source of carbon for photosynthesis, which provides the essential substrates for plant growth. However, elevating CO_2 concentration in the atmosphere is the main contributor to the increased global temperature and considered to be a major threat to the climate change (IPCC, 2007). The expansion of oil palm plantation in tropical peatlands, which mostly converts the forest and drains the water, contributes significantly to this global warming issue. The first 25 years cycle of oil palm plantation in tropical peatland including forest conversion was estimated to release 355 Mg C ha^{-1} (Germer and Saueborn, 2008). In the established oil palm plantation in tropical peatland, CO_2 emission is estimated at the range of 6–29 Mg C ha^{-1} yr^{-1} (Ishikura et al., 2018; Jauhiainen et al., 2001; Germer and Saueborn 2008; Dariah et al., 2014; Marwanto and Agus, 2014; Husnain et al., 2014; Murayama and Bakar, 1996; Hergoualc'h and Verchot, 2014; Melling et al., 2005). In addition, the emission factor, which is important for estimating and characterizing the emission sources, from oil palm plantation in peatlands is considered to be 11 Mg C ha^{-1} yr^{-1} (IPCC, 2014). The wide range of CO_2 emission rates reported in the previous studies indicates a large variation of environmental factors such as water table level, temperature, and peat moisture across the different peat quality. A better understanding on the relationship between CO_2 emission and factors affecting the emission is needed to define the appropriate mitigation action. Reducing CO_2 emission from drained tropical peatland is crucial to alleviate the global warming phenomenon.

Nutrient release during peat decomposition

Plant tissue is derived from atmospheric CO_2, water, and nutritional elements from soil (Gerhart and Ward, 2010). In peatland, nutrient cycles after the peat was once established depends on the limited nutrients pool among plants and peat (Driessen, 1978). The large pool of nutrients is preserved in the dead plant materials under water-saturated conditions. Exposing peat to gaseous oxygen causes organic matter decomposition, which releases these nutrients. Such a nutrient release occurred not only in the aerobic but also in the anaerobic conditions, when microbial decomposers require electron acceptors other than oxygen (Blodau et al., 2004; Mettrop et al. 2014; Conant et al. 2011; Kechavarzi et al. 2010; Ise et al. 2008; Clark et al. 2005). The degree of nutrient release during peat decomposition affects the nutrient availability for plant growth. At a certain amount, nutrients derived from peat decomposition are important for oil palm growth. However, the excessive peat decomposition rate declines the productivity of crop and the sustainability of the environment. A large amount of nutrient is lost from the established oil palm plantation as a result of active leaching under humid climates (Dislich et al., 2017; Driessen and Supraptohardjo, 1974). The high rainfall in tropics and drainage management in oil palm plantation causes the excessive nutrient loss to the lower area and declines the productivity of oil palm plantation. Fertilizer application is important to compensate the loss of nutrients, to support oil palm growth, and to decelerate the eventual decline of soil fertility, though nutrient leaching and loss still occurred (Allen et al., 2015; Kurniawan, 2016). The problem of nutrient loss in oil palm plantation could bring eutrophication of the downstream aquatic ecosystems as well (Frank et al., 2017; Rixen et al., 2010; Gibson et al., 2009; Meissner et al., 2008).

The intensive effort is required to achieve better understanding on the CO_2 emission and peat nutrients processes, which had high spatial and temporal variabilities due to complex interactions between biotic and abiotic factors. However, field studies on peat decomposition rate in tropical peatland have been focused on the CO_2 efflux from peat surface (IPCC, 2014), while study in subsoil is limited. Therefore, the CO_2 and nutrient release from subsoil and factors affecting the released are crucial to be elucidated for determining the appropriate technique to suppress CO_2 emission and offset the losses of nutrient.

1.2. Objectives of Study

The objectives of this study were: (1) to evaluate the peat decomposition rates in subsoil with reference to the CO_2 efflux potential from several depths of peat profile (Chapter 3), and (2) to evaluate the peat decomposition process in subsoil with reference to the concentration of chemical composition of soil solution (Chapter 4). Finally, general discussion is performed to evaluate the peat decomposition in subsoil through the relationship between peat profile CO_2 and chemical composition of soil solution (Chapter 5).

Chapter 2. Description of study sites

2.1. General characteristic of study sites

A field study was conducted 2 years from February 2015 to January 2017 in Sumatra and Kalimantan, two big islands of Indonesia where oil palm plantations are mainly distributed (Fig. 2.1).

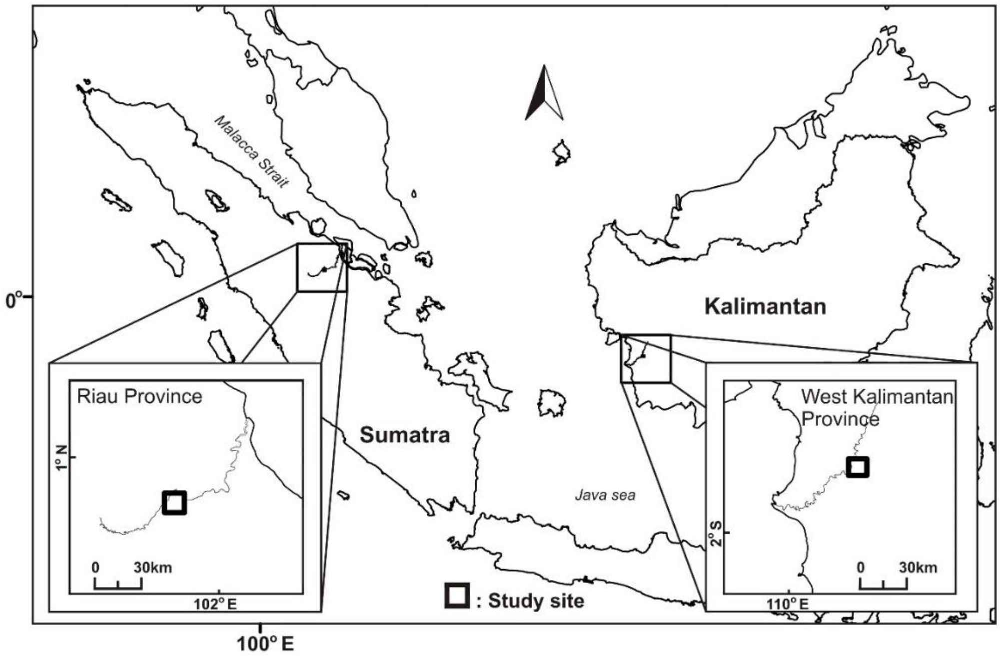

Figure 2. 1. Location of study sites in Sumatra and Kalimantan Islands, Indonesia.

The study site in Sumatra had 1,830 mm of annual rainfall, which was lower than that of the study site in Kalimantan (2,800 mm). Rainfall data in both sites was based on 4 years of monitoring data (2013–2016) from rainfall stations approximately 6 and 1 km away in Sumatra and Kalimantan, respectively (Fig. 2.2).

2.1.1. Site in Sumatra

The first site was located in the Siak Sri Indrapura District, Riau Province, Sumatra Island (0° 44′ N, 101° 43′ E), 10 m asl and approximately 67 km from the closest coastline. This study site was used for investigating peat decomposition in subsoil through both CO_2 efflux (Chapter 3) and soil solution study (Chapter 4).

The Siak River borders the western and northern parts of this peatland while the eastern and southern parts are bordered by hilly mineral soils. The peatland here is classified as inland basin peat (Anshari et al., 2010), in which peat dome may occur in flat forms. Peatlands in this study site are mainly used for oil palm plantation which was established in the year 2002. Most secondary forests in this site were diminished due to the fire disaster that occurred during September–October 2015. Shrubs were found beside oil palm plantations.

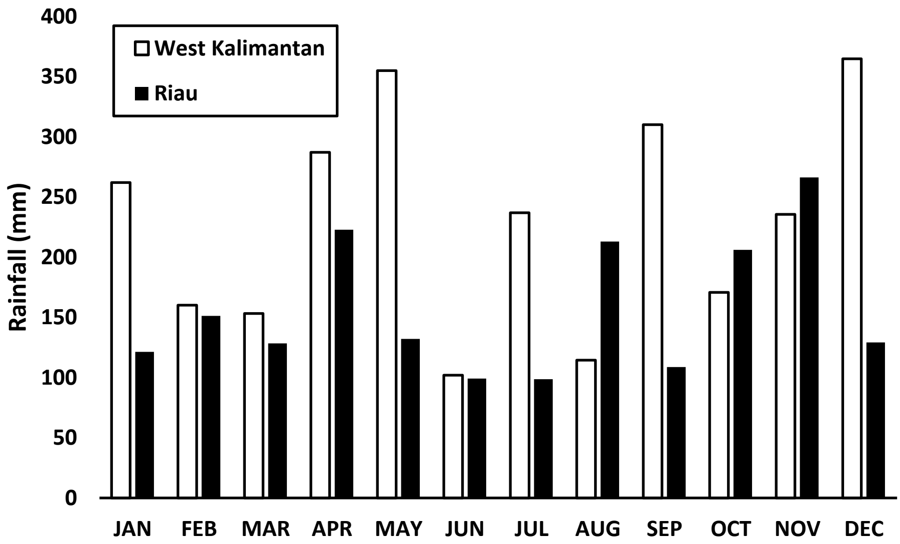

Figure 2. 2. Average of monthly rainfall data for West Kalimantan and Riau (year 2013–2016). Hollow bar indicates West Kalimantan site while solid bar indicates Riau site.

2.1.2. Site in Kalimantan

The second study site was located in the Ketapang District, West Kalimantan Province, Kalimantan Island (1° 37′ S, 110° 25′ E), 50 m asl, and approximately 41 km from the closest coastline. This site was used for investigating peat decomposition in subsoil through soil solution study (Chapter 4). The peat in this site is distributed between spotted undulating terrains or hills with mineral soil and classified as inland high peat (Anshari et al., 2010). This peatland extends in a northeasterly direction. The Pawan River borders the western part, while northern, southern and eastern parts are bordered by undulating terrains of mineral soils. Oil palm plantations, which established in year the 2009, dominated this peatland while riparian forests exist in a small area.

2.2. Description of sampling plot

Each sampling plot was in a different farm block (a management unit of oil palm cultivation). Farm blocks in both sites had a rectangular shape (300 × 1,000 m) and were surrounded by 5 m wide drainage canals, and 5 m wide roads in between. The densities of the oil palm trees in Riau and West Kalimantan sites were 133 and 130 trees ha^{-1}, respectively.

2.2.1. Study on peat decomposition rates in subsoil through CO_2 efflux from different depths of peat profile

Study on peat profile CO_2 release was conducted in Riau, at the same plantation site with soil solution study. A sampling plot was established in the middle of plantation to avoid the effects of canal water. During this study, the average rate of fertilizer application in this plot 144 kg N ha^{-1}, 46 kg P ha^{-1}, and 225 kg K ha^{-1}. Dolomite and lime, which supplied 216 kg Ca ha^{-1} and 54 kg Mg ha^{-1}, were also applied. Some microelements, such as Cu, B, and Zn, were added. Fertilizers were mostly applied randomly after the end of dry season, starting from October 2015 using a spreader machine.

2.2.2. Study on belowground peat decomposition through chemical composition of soil solution

Study on soil solution was conducted in two sites, Riau and Ketapang. In Riau, we established three oil palm plots (R1, R2, and R3) and one control plot consisting of shrub (RSh). Besides the dominant trees, *Macaranga sp.*, some species such as *Alstonia scholaris, Euodia ridleyi, Trema orientalis, S. palustris, N. biserrata,* and *Dicranopteris linearis* were found in the RSh plot.

In Ketapang, we had three oil palm plots (WK1, WK2, and WK3) and one control plot consisting of secondary forest (WKSF). Plant species in WKSF were *Macaranga* sp.*, Anacardium occidentale, Eugenia* sp.*, Archidendron pauciflorum, Endospermum* spp.*, Dillenia* sp.*, Nephelium* sp.*, Stenochlaena palustris,* and *Nephrolepis biserrata*. During this study, the average rate of fertilizer application in Ketapang was 168 kg N ha^{-1} in the form of urea, 35 kg P ha^{-1} of rock phosphate and triple superphosphate, and 146 kg K ha^{-1} of potassium chloride. Dolomite and lime were also applied, providing 84 kg Ca ha^{-1} and 9 kg Mg ha^{-1}. Microelements were added, similar with those in Riau. Fertilizers were mostly applied manually around the trunk of the plants after the end of dry season. Data on the fertilizer application in each Riau and Ketapang was collected from interviews and direct observations.

Chapter 3. Peat decomposition characteristics based on CO_2 production rates in different layers of peat soils

3.1. General

Tropical peatlands had an important role in the global carbon (C) cycle. Natural peatland is one of the largest C storages in the terrestrial ecosystem and could be a possible C sink. However, reclamation and land degradation has changed tropical peatlands, which now function as a huge source for atmospheric CO_2 (Herguoalc'h and Verchot, 2011; Murdiyarso et al., 2010). The dynamics of C reservoirs in peatlands depend on both the input of C from vegetation and the output through organic matter decomposition (Abrams et al., 2016; Dislich et al., 2016; Inglett et al., 2012). Study on CO_2 released from peat surfaces (CO_2 efflux) derived from peat organic matter decomposition in tropics is voluminous (Couwenberg et al., 2009; Jauhiainen et al., 2012). Unfortunately, the potential CO_2 released from peat profiles (CO_2 efflux potential/CO_2-EP) and its response to abiotic environmental dynamics in tropical peatlands are still poorly understood. A better understanding of peat decomposition rates in subsoil through CO_2 production is important, as it could be used to plan mitigation actions to avoid future C loss due to the exploitation of tropical peatlands.

The ratio of labile to recalcitrant organic matter determines the rate of decomposition processes (Berg, 2000). Labile C compounds, such as hemicellulose and cellulose, are preferably decomposed by microbes, unlike recalcitrant C compounds, such as lignin (Könönen et al., 2016). The duration of oil palm cultivation in peatland since deforestation and the start of drainage also determines the loss of labile C, which increases the amount of recalcitrant C and reduces the decomposition rate (Hoijer at al., 2012; Jauhiainen et al., 2016; Könönen et al., 2016).

Deforestation is a preliminary step to establish oil palm plantations and exposes peat surfaces to direct solar radiation, which elevates peat temperatures (Sano et al., 2010). The canopy of oil palm trees, especially in young plantations, provides less coverage for soil surfaces than natural forests do (Dislich et al., 2016). Temperature is one of the environmental factors that could affect peat decomposition (Inglett et al., 2012; Jauhiainen et al., 2012; Sihi et al., 2017). The CO_2 efflux from oil palm plantations with a less dense canopy cover would be higher than that of plantations with a denser canopy (Jauhiainen et al., 2014; Schrier-Uijl et al., 2013). However, peat decomposition could be less responsive to elevated temperatures because of desiccation (Hirano et al., 2014) and recalcitrant types of organic matter (Jauhiainen et al., 2016).

Water drainage to favor root growths and human access in oil palm plantations exposes peat to oxygen and leads to accelerated peat decomposition (Carlson et al., 2015). The lowering of the water table level usually increases the CO_2 efflux (Couwenberg et al., 2009; Furukawa et al., 2005; Hirano et al., 2014; Hooijer et al., 2010). However, a smaller response of the CO_2 efflux to water table fluctuations could be caused by the disconnection of capillary forces when the distance between the water table and the surface ground is too far (Ishikura et al., 2017; Wakhid et al., 2017).

Peat moisture conditions determine peat substrate decomposition, which releases CO_2 into the atmosphere (Jauhianen et al., 2008; Skopp et al., 1990). A laboratory experiment using tropical peat samples under different moisture content treatments suggested that both saturated and dry conditions of peat would reduce the CO_2 efflux (Husen et al., 2014). The optimum range of peat moisture content are needed to favor microbial activities, which are involved in the decomposition of organic matter (Kechavarzi et al., 2010).

We evaluate the peat decomposition in subsoil through CO_2 efflux and CO_2-EP from several peat depths in a mature oil palm plantation, and investigated the environmental factors controlling CO_2 efflux and CO_2-EP. We examined the fortnightly CO_2 efflux and CO_2-EP using the closed chamber method from four peat depths at 0, 10, 30, and 50 cm, respectively, with four replications. Environmental factors of soil moisture and temperature from similar peat depths were monitored hourly, while water table depth was monitored weekly.

3.2. Materials and Methods

3.2.1. Peat sampling

Peat sampling was conducted once in February 2015. For bulk density (BD) analysis, peat samples were collected from four peat depths (0–15, 15–30, 30–50, and 50–100 cm, respectively) using a 167 cm^3 ring sampler, with three replications. Disturbed samples were collected from the same four depths using a peat auger (Eijkelkamp, the Netherlands) for the determination of pH, electrical conductivity (EC), and ash content. A ratio of peat to deionized water of 1:10 was used to measure pH and EC using a glass electrode and an EC meter, respectively (LAQUA F-74 BW, Horiba). Ash content was determined using the loss of ignition (LoI) method under 550 °C in a muffle furnace. C content was calculated based on the mass loss during LoI.

3.2.2. Experimental design

A study plot was developed in the middle of the oil palm tree plantation, and between traffic paths and palm-frond windrows. Gas collection was carried out by sixteen chambers, each set at four different peat depths i.e., at 0, 10, 30, and 50 cm, using PVC (polyvinyl chloride) chambers with a diameter of 10 cm, which were inserted into holes prepared in advance with a hole auger (Fig. 3.1). Chamber caps were pre-equipped with glass thermometers and rubber septa for facilitating the use of syringes to collect gas samples. Each chamber was inserted 2 cm below the ground to avoid gas leakage and the remaining 20 cm (on the upper part of the chamber) were used for handling (Fig. 3.1). Four transects of holes/chambers installation were arranged in a square (1.5 × 1.5 m), and a sensor device to measure soil moisture and temperature was installed in the middle (Drill & Drop, Sentek Technologies). The roots surrounding the plot were not excluded. In this case, the CO_2 released was derived from autotrophic and heterotrophic respiration (total peat respiration).

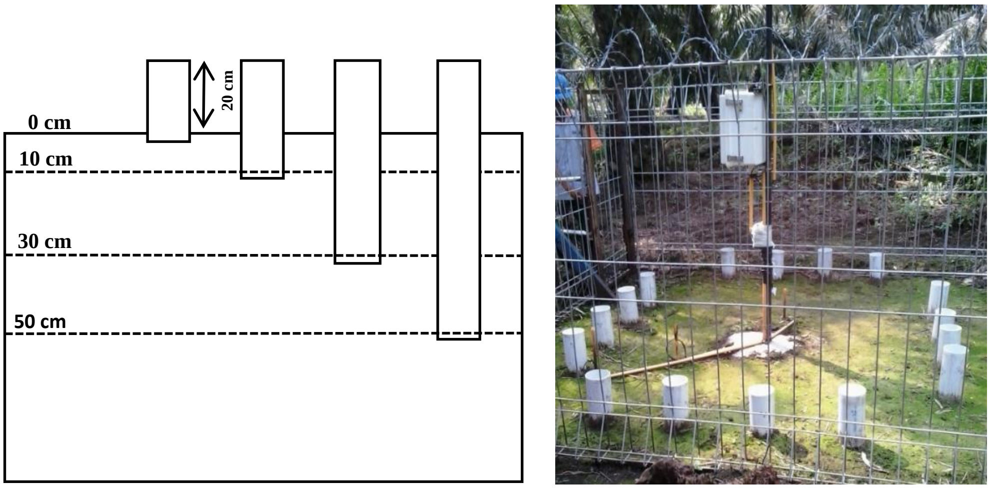

Figure 3. 1. Sketch of four chamber depth treatments of 0, 10, 30, and 50 cm with additional 20 cm length above the ground and 2 cm inserted into peat (left). Picture of the formation of 16 chambers, sensor device, and data logger installment in the site (right).

3.2.3. CO_2 gas sampling and measurement

The first gas sampling event was conducted one week after the chambers were installed, to avoid the effects of peat disturbance due to the holes made. Subsequently, regular samplings were conducted every two weeks. Gas sampling was conducted in the morning (8:00 am). Before collecting the gas samples, the chambers were removed from the hole and the gas that had accumulated inside the hole was gently flushed out and mixed up with ambient air by fanning manually for approximately three minutes. Subsequently, the chamber was installed into the hole again and closed by a cap at the top part of the chamber. The time when the chamber was closed with the cap was set as time zero (0 minutes) and the first gas sample was collected immediately using a 50 ml disposable plastic syringe. Subsequent gas samples were collected at 5, 10, and 15 minutes, respectively. The collected gas samples were all transferred into 30 ml vacuum vials to create over-pressured gas samples. The CO_2 concentration was measured using an infrared CO_2 analyzer (ZFP9AA11, Fuji Electric, Tokyo Japan), with a C-R6A detector (Shimadzu, Kyoto, Japan), and using N_2 carrier gas. The concentration of CO_2 for each vial was derived from two replicates of peak area measurement. The release rate (F) of CO_2 (Mg C ha^{-1} yr^{-1}) was calculated using the following equation (IAEA, 1992):

$$F = (dC/dt) \times h \times \rho \times (273.2 / (273.2 + T_c))$$

Where *dC*/*dt* is the change of CO_2 concentration from interval sampling (ppm min^{-1}), *h* is the height of chamber (m), ρ is the density of the CO_2 gas (g m^{-3}), and T_c is the temperature inside of the chamber (°C).

3.2.4. Environmental factors measurement

Peat moisture and temperature at the incremental depths of 0–10, 10–20, 20–30, 30–40, 40–50, and 50–60 cm were monitored hourly using data logger (CR200, Campbell Scientific Inc.). Where necessary, we averaged the values of sensor data from two depths to fit with the depth of CO_2 sampling. Daily rainfall was monitored using a rain gauge installed approximately 6 km from the site. The water table level was monitored manually weekly using 1.5 m perforated PVC pipes, which were installed 1 m from the square plot. The distance between the ground surface and the water table level beneath the ground was expressed as 'depth', or a negative value in the figures.

3.2.5. Statistical analysis

Spearman's correlation analysis was conducted to evaluate the relationship between CO_2 released and environmental factors (water table, soil moisture, and soil temperature) and among CO_2 released from different peat depths. Statistical analysis was conducted using Statistica® 7.0 (Statsoft Inc. Oklahoma, USA).

3.3. Results

3.3.1. Peat properties

The peat properties of the study plot are presented in Table 3.1. Peat at the surface layer had a higher pH, BD, and ash content than at lower layers, while C content was lowest.

3.3.2. Rainfall and water table fluctuation

The fluctuation of rainfall and the water table level are shown in Fig. 3.2. The study site experienced a dry season in the period of June–October 2015 and El Niño occurred towards the end of the dry season (September–October 2015).

Table 3. 1. Peat properties of the study site.

Properties	Soil depth (cm)			
	0–15	15–30	30–50	50–100
pH H_2O (1:10)	4.4	4.2	3.9	3.8
EC (µS cm^{-1})	102.4	147.1	89.5	73.0
BD (g cm^{-3})	0.25	0.14	0.13	0.13
Ash content (%)	14.8	5.8	4.3	3.8
C content (%)	45.4	50.2	51.0	51.8

BD= bulk density; EC = electric conductivity. All values are dry weight base.

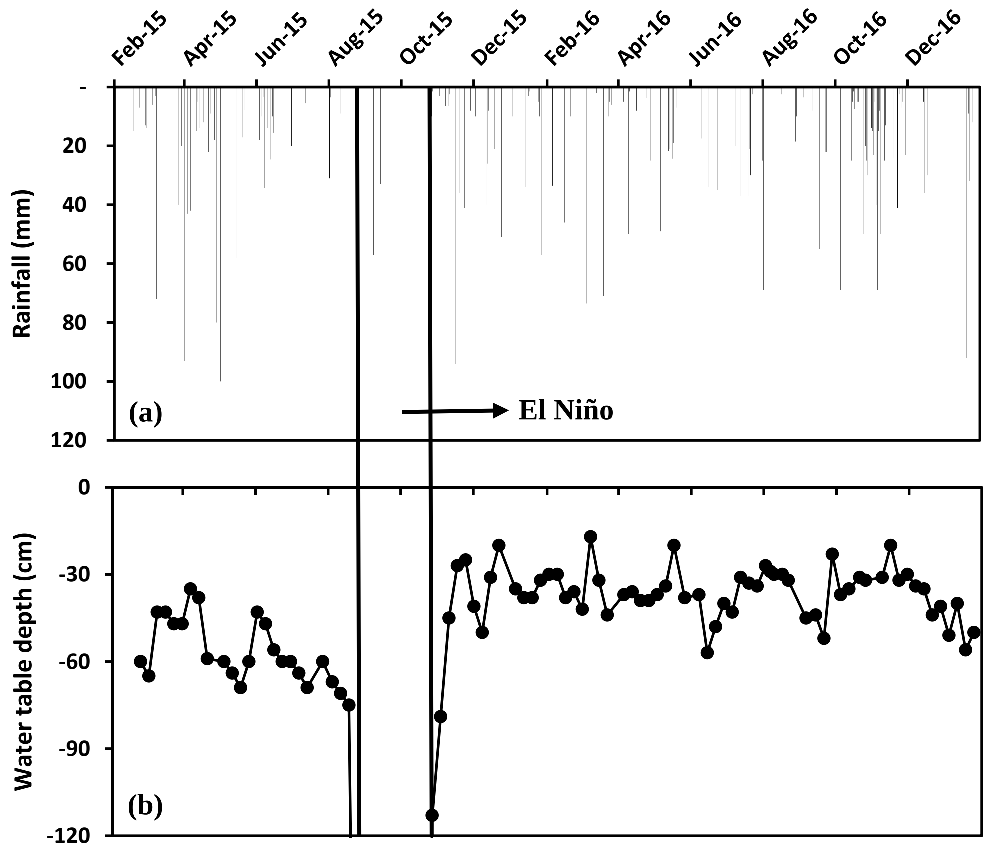

Figure 3. 2. Daily rainfall (a) and weekly water table level (b) in the study site from February 2015 to October 2016. El Niño occurred during September–October 2015.

During the prolonged dry season of El Niño, the water table level dropped to below a depth of 150 cm. The end of the El Niño effect, in November 2015, was signified by a series of rainfall events (Fig. 3.2a) and an increase of the water table level (Fig. 3.2b). The average water table level increased from 52 cm depth in the 1st year of the study (February 2015–January 2016), when the El Niño event occurred, to 36 cm depth in the 2nd year of the study (normal year, February 2016–January 2017).

3.3.3. Peat temperature and moisture fluctuation

The fluctuation of peat temperature and moisture are shown in Fig. 3.3. In the normal season, the temperature in the upper peat layer was usually higher than in the lower peat layer (Fig. 3.3a). However, during El Niño, this order was inverted and the peat temperature at the topsoil was lower than that at the subsoil. Furthermore, the fluctuation in peat moisture (Fig. 3.3b) is likely to be similar to the fluctuation in the water table level (Fig. 3.2b). During El Niño, peat moisture in the topsoil decreased more rapidly than in the subsoil. Peat moisture then increased in the end of El Niño, coincident with a series of rainfall events and an increase in the water table level.

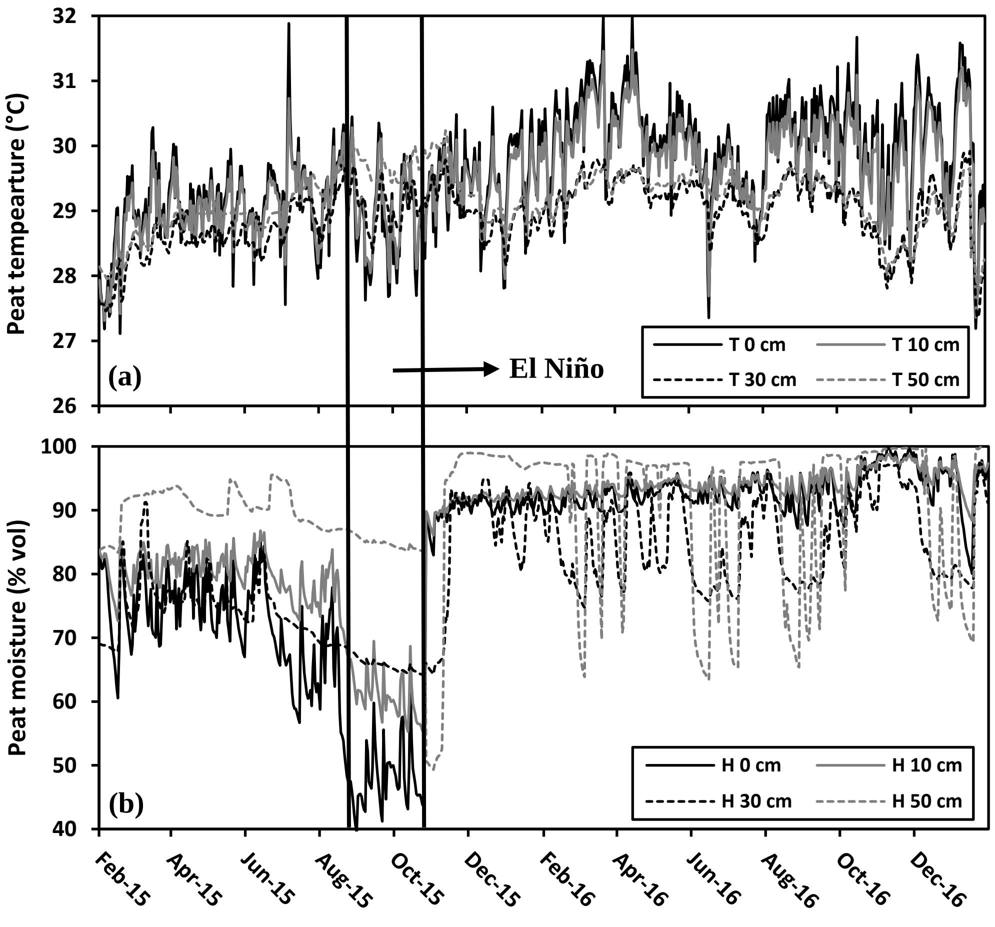

Figure 3. 3. Daily peat temperature (a) and moisture (b) from peat depths of 0, 10, 30, and 50 cm in the study site.

3.3.4. The nature of CO_2 measured in this experiment

In this study, CO_2 released from 0 cm refers to CO_2 efflux, where CO_2 gas is derived from both heterotrophic and autotrophic respiration released from solid peat to the atmosphere. However, due to the complex interaction of CO_2 sources from the deeper chamber, the CO_2 released from 10, 30, and 50 cm was considered as CO_2 efflux potential (CO_2-EP). Although the CO_2-EP calculation may involve some uncertainty because it possibly involves concentrated CO_2 (or the CO_2 accumulated previously) due to a low gas diffusion rate, it could be a potential estimate of the OM decomposition rate during the measuring time. The CO_2 produced in the subsoil could be transported to the soil surface and subsequently contribute to the CO_2 efflux from the soil surface under favorable moisture conditions.

3.3.5. The fluctuation of CO_2 efflux and CO_2-EP

The fluctuation of CO_2 efflux and CO_2-EP are shown in Fig. 3.4. In general, the concentration of CO_2 efflux was much lower than CO_2-EP. At the beginning of the dry season, in June 2015, the CO_2 efflux and CO_2-EP increased. Surprisingly, CO_2 efflux then decreased during the El Niño period while CO_2-EP from subsoil increased.

3.4. Discussion

3.4.1. Influence of El Niño on peat decomposition

The warmer temperatures across the tropical Pacific Ocean in 2015 resulted in abnormally dry year of a strong El Niño in Indonesia (Schiermeier, 2015). At that time, intense fires occurred in very dry peatland and these fires were followed by thick smoke pollution, which became a regional catastrophe (Field et al 2016; Parker et al., 2016). El Niño had a strong effect on the water table level and soil moisture in our study site (Fig. 3.2b and 3.3b). The warmer temperatures caused by El Niño in 2015 in Indonesia were not associated with peat temperature at the topsoil in the study site (Fig. 3.3a). The CO_2 efflux and CO_2-EP exhibited different patterns during the El Niño event where the CO_2 efflux tended to decrease, while CO_2-EP at 30 and 50 cm peat depths tended to increase (Fig. 3.4a, b). Due to the uniqueness of these variables, which may not represent a regular pattern, we exclude the El Niño year (1st year of the study, February 2015–January 2016) from the further discussion section.

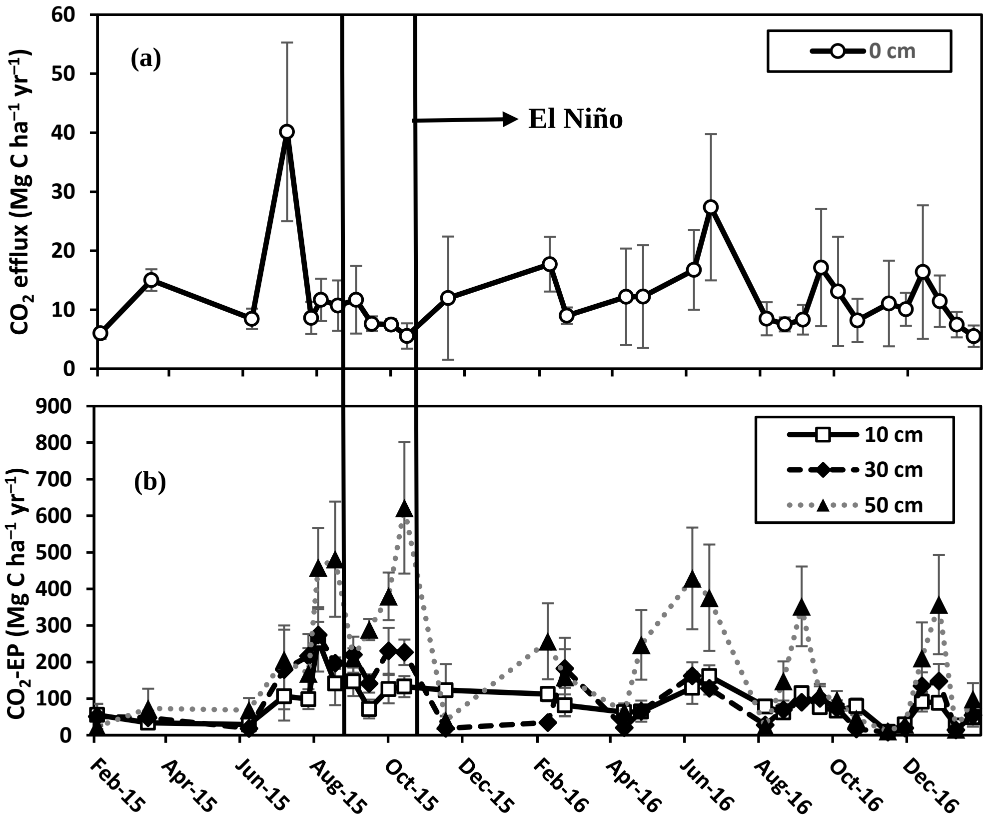

Figure 3. 4. Fluctuation of CO_2 efflux from the peat surface (a) and CO_2-EP from 10, 30, and 50 cm soil depth (b) during this study period. The dot represents the mean CO_2 efflux (n = 4). Error bar indicates standard error.

3.4.2. Factors affecting CO_2 efflux and CO_2-EP

The analysis of the 2nd year of the study (normal year, February 2016–January 2017) indicates that only CO_2-EP at both 30 and 50 cm peat depths were significantly correlated with peat moisture and water table level (Table 3.2). Lower peat moisture and water table levels were correlated with a higher CO_2-EP at both 30 and 50 cm peat depths. However, the amount of CO_2 released from both 0 and 10 cm peat depths (topsoil) was not correlated with environmental factors, which is not consistent with several previous studies in tropical peatlands (Furukawa et al., 2005; Hirano et al., 2012; 2007; Inubushi et al., 2003; Jauhiainen et al., 2014; 2016).

Table 3. 2. The r of Spearman's rank order correlation between CO_2 release and environmental factors of soil temperature, soil moisture, and water table at different depths of the 2nd year study.

Depth (cm)	CO_2 *vs* soil temperature (n=18)	CO_2 *vs* soil moisture (n=18)	CO_2 *vs* water table level (n=18)
0	–0.19	–0.09	–0.04
10	–0.07	–0.22	–0.26
30	0.19	–0.69***	–0.56**
50	0.28	–0.59**	–0.45*

Asterisk (*) indicates significant correlation at $p < 0.1$, (**) at $p < 0.05$, and (***) at $p < 0.01$; *vs* means versus.

CO_2 efflux and CO_2-EP in this study was not correlated with peat temperature (Table 2). Previous studies have tried to examine whether recalcitrant (Bosatta and Ågren, 1999; Hilasvuory et al., 2013; Wagai et al., 2013) or labile organic matter (Liski et al. 2000; Rey and Jarvis 2006) is less sensitive to temperature, and this study agrees that the recalcitrant organic matter affected the less sensitive of peat to temperature. Peat in the study site had advanced decomposition, which reduces most of the labile organic matter in the oxidic layer, due to the long time since deforestation, water drainage, and crop cultivation. The higher pH, BD, and ash content, and lower C content in topsoil than in the subsoil indicates the advanced decomposition of organic matter (Table 3.1). An increase in peat recalcitrant C over time, due to intensive decomposition and lack of organic matter input, was also reported by Könönen et al. (2016) in drained tropical peatlands in West Kalimantan. A study at the laboratory incubation scale using peat samples from tropical peatland also confirmed that the CO_2 production rate depends on the existing amount of the labile C fraction, and the CO_2 production rate increases with increasing labile C (Jauhiainen et al., 2016).

CO_2 released from the topsoil was also not correlated with peat moisture (Table 3.2), which suggests that dried and recalcitrant peat possibly reduces the microbial activity in the peat, and thereby affects the decomposition of organic matter. Under high rates of evaporation, which are caused by seasonal variation, peat desiccation may occur and result in low CO_2 efflux at that time (Hirano et al., 2014). The drying of peat in long cultivated peatlands is considered to be an irreversible condition, and it is difficult to be recovered, even under rewetting treatment. Moreover, considering the strong relationship between peat moisture content and water table level (Carlson et al., 2015), CO_2 efflux was not only poorly correlated with peat moisture, but also with the water table (Table 3.2).

The significant correlation among CO_2 released along the peat profile (Fig. 3.5) suggests that CO_2 efflux is not affected by the environmental factors tested in our study but CO_2 gas diffusion from deep layers of peat. The declining correlation gradient from the bottom to the surface layer (Fig. 3.5) indicates that the higher concentration of CO_2 in the deeper peat layer is gradually transported to the upper layer, and results in continued release of CO_2 into atmosphere as CO_2 efflux (Clymo and Bryant, 2008; Panikov et al., 2007).

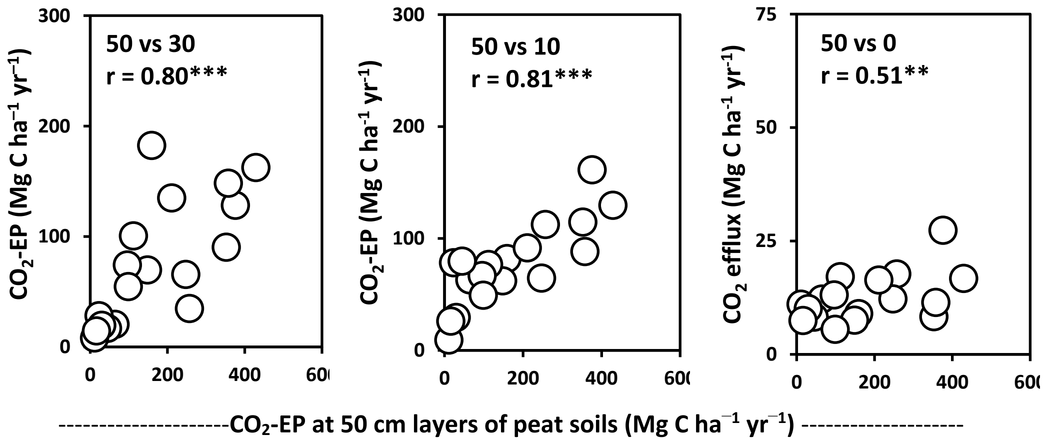

Figure 3. 5. Correlation between CO_2 released from different depths of peat in the normal year (n = 18). The horizontal (*x*) axis represents CO_2-EP at 50 cm depth, while the vertical (*y*) axis represents CO_2 released from 30, 10, and 0 cm peat depth, from left to right, respectively. The circle symbol represents a daily average (n = 4). Asterisks (**) indicate significant correlation at $p < 0.05$ while (***) indicates significant correlation at $p < 0.01$.

3.4.3. Annual CO_2 efflux and CO_2-EP

The amount of CO_2 released from both 0 and 10 cm peat depths, in a normal year (without El Niño), did not depend on environmental factors (Table 2). Thus, annual CO_2 from those depths was simply calculated using the averaging method based on actual measurements (n = 72 for each depth). On the other hand, CO_2-EP at both 30 and 50 cm peat depths were calculated by equations presented in Fig. 3.6. These equations were derived from the linear relationship between CO_2 and peat moisture, where y = CO_2-EP and x = hourly moisture content. CO_2-EP could be a potential estimate of OM decomposition rate during the measuring time, however, as stated in the results section that the CO_2-EP calculation might involve some uncertainty because it possibly includes the concentrated CO_2 (or CO_2 accumulated previously) due to a low gas diffusion rate.

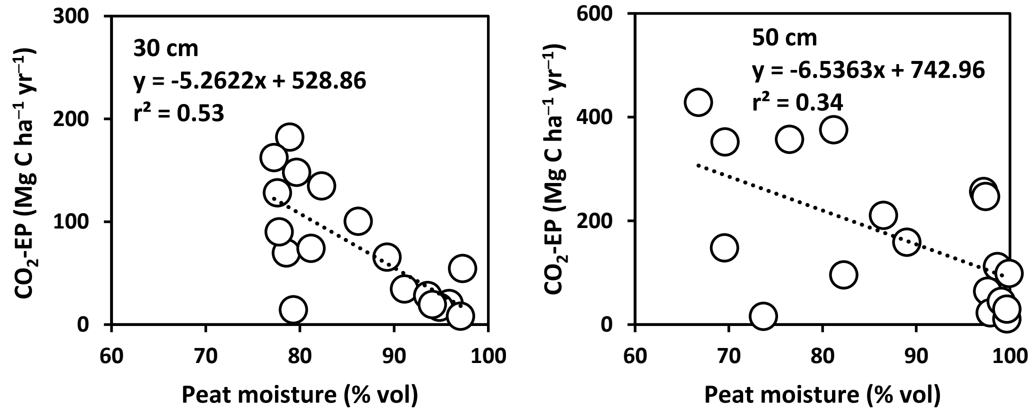

Figure 3. 6. Linear relationship between CO_2-EP (Mg C ha^{-1} yr^{-1}) and peat moisture (% vol.) for 30 (left) and 50 cm peat depth (right), respectively. The circle symbol represents a daily average (n = 4). The vertical axis of CO_2-EP is presented on a different scale.

Annual CO_2 efflux from this study was calculated as 12.2 ± 1.5 (means ± standard error) Mg C ha^{-1} yr^{-1}, which is slightly higher than CO_2 emission factor previously determined from peatland under oil palm plantation (11 Mg C ha^{-1} yr^{-1}, IPCC, 2014). Furthermore, the annual CO_2-EP follows the order of 10 < 30 < 50 cm peat depth with 77, 80, and 154 Mg C ha^{-1} yr^{-1}, respectively. The greater CO_2-EP in the deeper peat would be due to the higher amount of labile organic matter at such depths. The peat has experienced long cultivation after reclamation and drainage started, and, as such, most of the labile fraction of organic matter at the top soil layers was lost. Currently, the active decomposition layers of peat are shifting to the lower layers, at which the CO_2-EP is still high and occasionally high amounts of CO_2 are released when the water table and peat moisture are low.

3.4.4. Comparison between CO_2 efflux in this study and another published study

The annual CO_2 efflux found by other studies in tropical peatland under oil palm plantation, which was also derived from total respiration (autotrophic and heterotrophic), is presented in Table 3.3. All reference studies are based on one-year measurements. The low CO_2 efflux from mature oil palm plantations (≥ 14 years old) under different water table levels was found by both Marwanto and Agus (2014) and this study (Table 3.3; Fig. 3.7). On the other hand, four studies conducted during the first cycle of young oil palm plantations (≤ 8 years old) (Comeau et al., 2013; Dariah et al., 2014; Husnain et al., 2014; Melling et al., 2005), had a linear relationship between CO_2 efflux and water table depth ($R^2 = 0.80$). This suggests that the CO_2 efflux from the older oil palm plantations is affected more by the timing of cultivation than by the water table level. The subsequent decrease in the estimated CO_2 efflux from oil palm plantations since land clearing and establishment of drainage was also reported by Hooijer et al. (2012), based on peat subsidence components. This study confirms the hypothesis that the active decomposition layer of peat under mature oil palm plantation is in subsoils. The CO_2 is occasionally released from the surface, reflecting the moisture condition of subsoils. The longer cultivation of oil palm plantation in peatland mostly reduces the amount of decomposable organic matter in peat.

Table 3. 3. The average of CO_2 efflux from several published studies in tropical peatland under oil palm plantation.

References	Annual CO_2 efflux (Mg C ha^{-1} yr^{-1})	OP age (year)	Average water table level (cm)	Locations
This study (Feb16 – Jan17)	12.2	14	-36	Riau
Dariah et al., 2014	10.4	6	-55	Jambi
Husnain et al., 2014	18.0	4	-72	Riau
Melling et al., 2005	16.6	4	-60	Sarawak
Comeau et al., 2013	28.4	7	-76	Jambi
Marwanto and Agus, 2014	12.6	14	-91	Jambi

OP = oil palm plantation

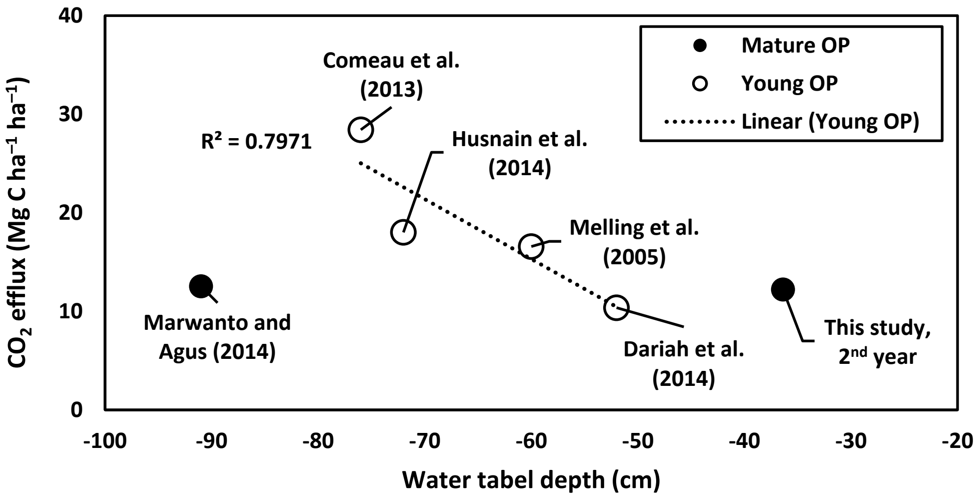

Figure 3. 7. A linear model of CO_2 efflux (Mg C ha^{-1} yr^{-1}) and water table depth (cm) from four published studies in young oil palm plantations of tropical peatlands (Comeau et al., 2013; Dariah et al., 2014; Husnain et al., 2014; Melling et al., 2005). Mature OP means oil plantations were ≥ 14 years old, while young OP means oil plantations were ≤ 7 years old.

3.4.5. Suggestions for reducing CO_2 efflux

Reducing CO_2 efflux from drained tropical peatlands is important for alleviating the global atmospheric CO_2 concentration. The CO_2 efflux from the peat surface under mature oil palm plantations is considered to be less affected by environmental factors. Instead, the CO_2 efflux from the mature oil palm plantations is mainly derived from peat decomposition of subsoil. Thus, suppressing peat decomposition of the deep peat profile is crucial for mitigating CO_2 efflux. This study showed that CO_2-EP is strongly affected by peat moisture content where CO_2-EP decreased in the situation of the subsoil became saturated. Therefore, maintaining a high water table level, even during the dry season, is fundamental to reduce CO_2 efflux. This practice may not completely halt the loss of C into the atmosphere, but at least decelerates the eventual peat degradation. Moreover, organic matter along the peat profile is considered to be vulnerable and its exploitation should be avoided.

3.5. Conclusion

The annual CO_2 efflux from this study site was calculated as 12.2 ± 1.5 Mg C ha^{-1} yr^{-1} and the fluctuation in CO_2 efflux was not affected by environmental factors. The longer period of reclamation, water drainage, and cultivation of mature oil palm plantations reduces the peat decomposable organic matter in surface and increases the amount of recalcitrant C. Despite an uncertainty associated with the CO_2-EP calculation, this effort provides insight into the incremental concentration of CO_2 along the peat profile. The rate of CO_2-EP is higher in the deeper peat layer, possibly because of the downward shifting of profile distribution of active decomposition layer. Currently, the active decomposition layer is subsoils and CO_2 production from the deeper layer might be gradually transported to the upper layer and contribute to the CO_2 efflux. This study emphasizes the importance of water management for reducing CO_2 efflux from tropical peatlands under oil palm plantation. Moreover, the exploitation of peatland by exposing the peat profile to aerobic conditions is harmful.

Chapter 4. Seasonal fluctuation of soil solution composition with special reference to peat decomposition

4.1. General

Peat is formed by the accumulation of dead plants that decompose very slowly under waterlogged conditions. Peatland is less favorable for crop production (Agus and Subikse 2008; Haraguchi et al. 2000; Driessen 1978). However, because of the limited area of productive land with mineral soils, 14.9 Mha of Indonesian peatlands (Ritung et al. 2011) are considered potential areas to produce agricultural crops, including oil palm plantations. Understanding the peat decomposition in subsoil through chemical composition of the soil solution in peatlands is important for not only maintaining high oil palm productivity, but also preventing environmental degradation due to acidification, eutrophication, and greenhouse gas emissions (Abrams et al. 2016, Cusell et al. 2013). Unfortunately, information on the chemical composition of tropical peatlands is limited.

The chemical composition of the soil solution is affected by seasonal variations in water table levels. During the dry season, water table levels decrease because of high evapotranspiration (Hirano et al. 2014; Ishii et al. 2016). The loss of water from the peat leads to increases in the oxygen supply and temperature, resulting in organic matter decomposition and the release of nutritional elements such as N, P, K, and S (Mettrop et al. 2014; Conant et al. 2011; Kechavarzi et al. 2010; Ise et al. 2008; Clark et al. 2005; Koerselman et al. 1993). During this season, the pH of the soil solution decreases in the aerobic layer because of peat oxidation, while the pH in the anaerobic layer increases because of reductive reactions (Loeb et al. 2008; Adamson et al. 2001). Under anaerobic conditions, alkalinity increases through the microbial reduction of Fe^{3+}, SO_4^{2-}, and NO_3^-, which is accelerated under increased temperatures (Cusell et al. 2015; Baker et al. 1986).

Rainfall affects the transportation of nutritional elements and leads to the depletion of nutrients in peatlands. The leaching of the nutritional element, K^+, by rainfall occurs in tropical peatlands (Funakawa et al. 1996). On a laboratory scale, NO_3^- can be flushed from peat using rewetting treatments (Kleimeier et al. 2014). Nutrient depletion occurs in drained peatlands through leaching and biomass removal (van Beek et al. 2007; van Duren and van Andel 1997; Driessen 1978). This leached nutrient as well as organic acids can be transported downstream and causes eutrophication and acidification (Frank et al. 2017; Rixen et al. 2010; Gibson et al. 2009; Meissner et al. 2008). In addition, rainfall is the main factor contributing to water table rise in peatlands which affected to the increasing peat respiration (Ishikura et al. 2017). Water table movement influences reductive and oxidative reactions in peatlands.

This study aimed to evaluate the peat decomposition process in subsoil with reference to the concentration of chemical composition of soil solution. We examined the composition of soil solutions across seasonal variation in peatland sites of Kalimantan and Sumatra, Indonesia. Soil solution sampling was conducted fortnightly at two soil depths. Environmental factors of rainfall and water table levels were monitored. We hypothesized that seasonal variations in rainfall and water table movement would affect the fluctuations in soil solution composition.

4.2. Materials and Methods

4.2.1. Sampling design

A peat auger with swing blade was used to collect peat samples and determine peat depths (Eijkelkamp). For chemical analyses, peat samples were collected at 0–15, 15–30, and 30–50 cm depths, and then every 50 cm. Only the results of solid peat sample from 0 to 250 cm depths are shown in this paper. Undisturbed peat samples for bulk density analysis were collected in triplicates using a 167 cm^3 ring sampler. Bulk density was analyzed for the 0–15, 15–30, and 30–50 cm depths.

Polyvinyl chloride pipes with a diameter of 10 cm were used for soil solution sampling. The pipe had a 20 cm long perforated section at the bottom to enable the entry of the soil solution. Plastic nets with 1 mm sized mesh were used to cover the openings to filter coarse materials. The pipes were placed in the middle of the farm block to eliminate the effects of the drainage canal. The pipes were installed to reach 50 and 200 cm depths between oil palm trees to minimize the effect of roots. The pipes were 50 cm above the peat surface and were always covered with a cap, except during sampling, to avoid contaminants such as water from rainfall and insects. Two pipes were installed in October 2015 and one additional pipe in February 2016 for each depth and plot. Soil solution samples were collected fortnightly from the pipes. To collect soil solution samples, a hose was inserted and the solution sample at the bottom of pipe was sucked, the initial part was disposed and the 50 ml of remained sample was directly transferred into bottle. Soil solution samples were kept in the tightly closed, airless bottles at 4 °C until measurements.

4.2.2. Water table monitoring

Water table depth was measured using pipe which installed in the center of each plot. The material and diameter of pipe were similar to the pipe used to soil solution sampling. The pipe had a perforated section along 1.5 m length which inserted into the peat with the remaining 0.5 m kept above ground. The bottom part of pipe was remained to be uncovered. Water table level was measured using a meter stick manually on a weekly basis.

4.2.3. Analytical method

Solid peat samples were air dried and sieved through 2 mm mesh for chemical analysis and 0.5 mm mesh for ash content determination. pH and electrical conductivity (EC) were determined using a glass electrode and an EC meter, respectively (LAQUA F-74 BW, Horiba), with a peat to deionized water ratio of 1:10. Total Ca, Mg, K, and Na contents in peat samples were determined after their digestion using hydrofluoric, sulfuric, perchloric, hydrochloric, and nitric acid (Hossner 1996). The solutions were then measured using inductively coupled plasma atomic emission spectroscopy (ICPE-9800, Shimadzu). All the chemical properties of peat samples are given on an oven dried basis.

The pH and EC of soil solution samples were measured using the same methods described above. After these measurements, the samples were filtered through 0.45 µm syringe filters (Sartorius). The concentration of dissolved organic carbon (DOC) was measured using a total carbon analyzer (TOC-L, Shimadzu). The concentration of Ca, Mg, K, and Na in soil solutions were determined using an atomic absorption spectrophotometer (AA-7000, Shimadzu), while concentrations of NO_3^- and SO_4^{2-} were determined using a high-performance liquid chromatograph (HIC-6A equipped with a CDD-6A conductivity detector and Shim-pack ICC-A1; Shimadzu).

4.2.4. Statistical analysis

The difference between the chemical compositions of the soil solutions in the oil palm plots taken from 200 cm depths at the two study sites and the difference between those from 50 and 200 cm depth in each site were tested using a *t*-test. A Tukey's honest significance difference test was used, after an ANOVA, to test the differences in ion concentrations of samples collected from the same depths among plots, within each study site. All statistical analysis was conducted by Statistica® 7.0 (Statsoft Inc. Oklahoma, USA).

4.3. Results

4.3.1. Physicochemical properties of the peats

Peat bulk density, pH, EC, ash content, and total element content in West Kalimantan and Riau are shown in Table 4.1. The total Ca content of solid peat was lower in West Kalimantan than in Riau. The other cations concentration of Mg and Na in West Kalimantan were also lower than Riau, while K concentration was unclear.

4.3.2. The mean concentration of soil solution composition

Ion concentrations of soil solutions from oil palm plantation plots, three in each site of West Kalimantan and Riau, are shown in Fig. 4.1a. This analysis was only conducted for 200 cm depths, as the number of samples collected at 50 cm depth in Riau was too small because of low water table depths. pH, Ca^{2+} and Mg^{2+} concentrations (pH_{200cm}, Ca_{200cm} and Mg_{200cm}) were significantly lower in West Kalimantan than in Riau, whereas Na^+ and K^+ (Na_{200cm} and K_{200cm}) were significantly higher.

Table 4. 1. Properties of selected peat profiles in the West Kalimantan and Riau sites.

Depth	BD	pH (H_2O)	EC	Ash content	Total element			
					Ca	Mg	Na	K
(cm)	(g cm^{-3})		(μS cm^{-1})	(%)	--------($cmol_c$ kg^{-1})--------			
West Kalimantan								
0–15	0.25	4.2	141	6.1	1.0	0.3	0.1	2.9
15–30	0.18	3.8	187	3.7	0.9	0.3	0.2	2.2
30–50	0.14	3.5	201	2.5	1.5	0.4	0.4	1.8
50–100	-	3.6	96	2.3	0.9	0.3	0.3	1.9
100–150	-	3.4	147	1.8	0.5	0.3	0.1	1.7
150–200	-	3.5	182	1.9	0.6	0.3	0.1	1.7
200–250	-	3.5	104	2.8	1.0	0.3	1.0	2.8
Riau								
0–15	0.28	4.3	144	13.2	7.9	2.2	0.6	2.1
15–30	0.18	4.1	71	8.1	5.9	2.3	0.3	2.0
30–50	0.16	3.8	144	3.5	3.0	1.1	0.9	2.0
50–100	-	3.6	179	2.7	2.8	0.9	11.8	0.9
100–150	-	3.3	211	1.6	1.5	0.5	11.4	0.8
150–200	-	3.6	212	2.5	1.9	0.7	12.5	1.7
200–250	-	3.5	214	2.4	1.5	0.6	12.3	0.8

BD: bulk density, EC: electrical conductivity.

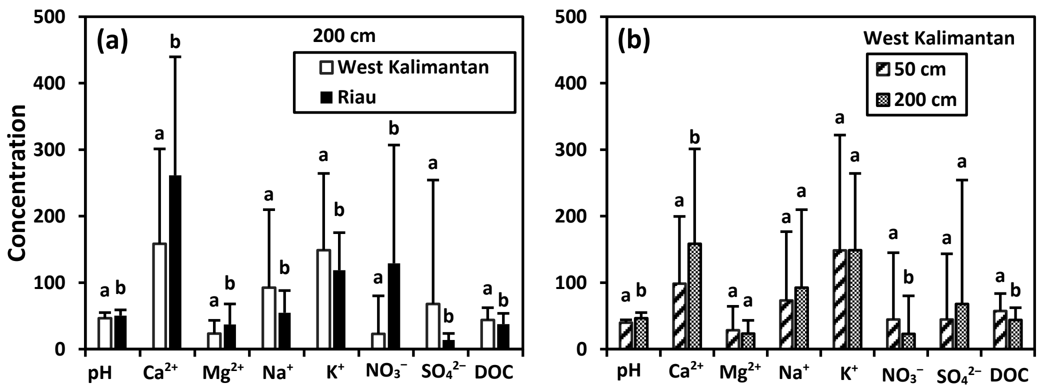

Figure 4. 1. The means of chemical composition of soil solution in oil palm plantations. All unit is μmol L^{-1} except for pH (no unit, multiply by 10) and DOC (cmol L^{-1}). Error bar indicates standard deviation. The same character indicates no significant difference between West Kalimantan and Riau in 200 cm depth (a) and between 50 and 200 cm depth in West Kalimantan (b).

NO_3^- concentration at 200 cm depth ($NO_{3\text{–}200cm}$) was significantly lower in West Kalimantan than in Riau, while SO_4^{2-} and DOC concentration ($SO_{4\text{–}200cm}$ and DOC_{200cm}) were significantly higher. The chemical composition of soil solution from the depth of 50 and 200 cm in West Kalimantan are presented in Fig. 4.1b.

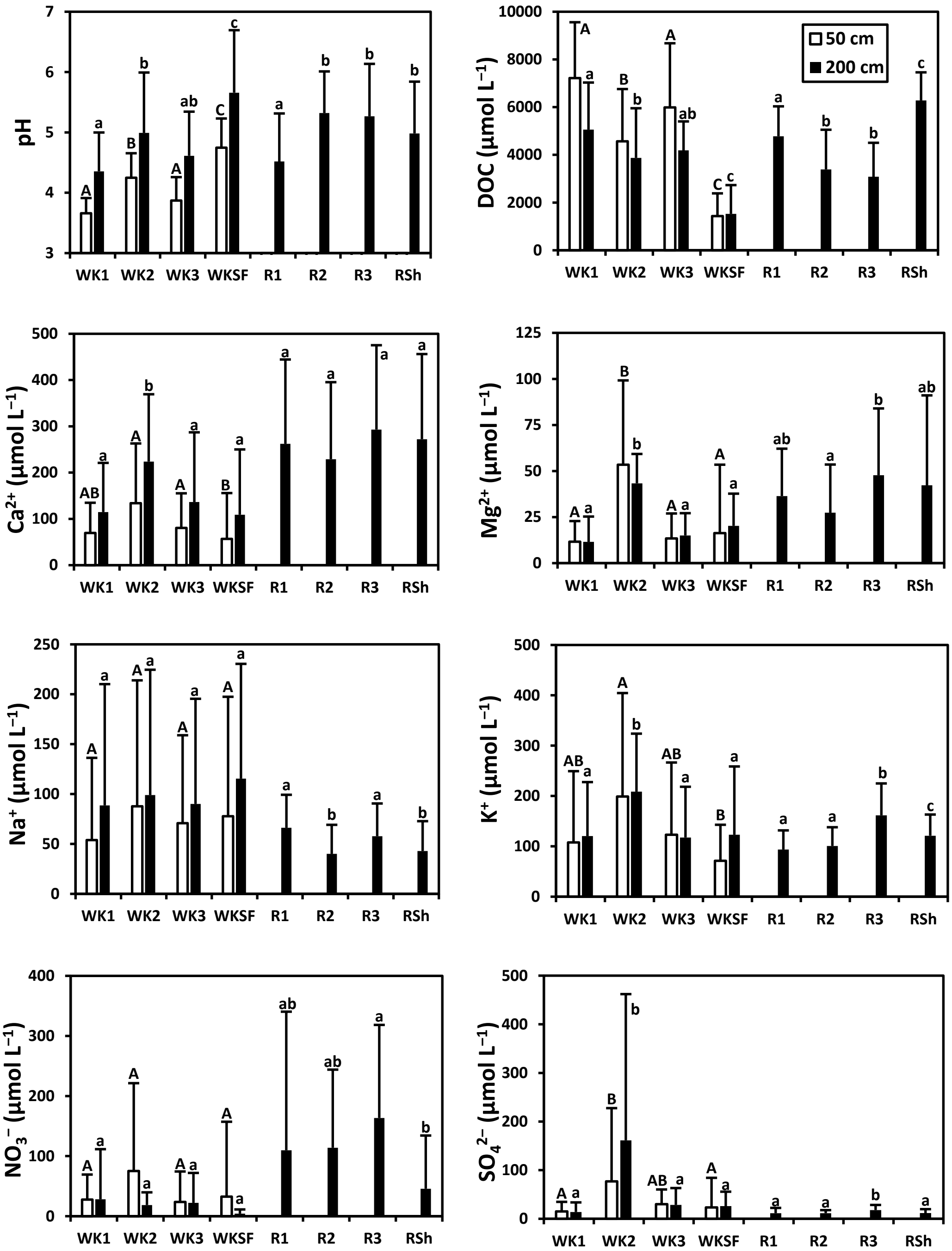

Figure 4. 2. The means of pH, DOC, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, NO_3^{-}, and SO_4^{2-} concentrations in the soil solution. The hollow bar (□) represents the 50 cm depth, while the solid bar (■) represents the 200 cm depth. Error bar indicates standard deviation. The same characters indicate no significant difference among plots within each study site, where the uppercase letter for 50 cm depth while lowercase for 200 cm depth. The absence of chemical composition in 50 cm depth in Riau because of the less number of samples.

Soil solution at the depth of 50 cm had pH and Ca^{2+} concentration (pH_{50cm} and Ca_{50cm}) significantly lower than 200 cm. Concentration of NO_3^- and DOC at 50 cm depth (NO_{3-50cm} and DOC_{50cm}) were significantly higher than 200 cm depth.

In WKSF, soil solutions at 50 and 200 cm depths had higher pH levels and lower DOC concentrations than those in the oil palm plantation plots in West Kalimantan (Fig. 4.2). However, pH levels at 200 cm depths in RSh did not significantly differ from those of oil palm plots in Riau. In general, pH levels at 50 cm were lower than pH_{200cm}, whereas the DOC concentration at the 50 cm depth was higher than that the 200 cm depth (Fig. 4.2).

Cation and anion concentrations of soil solutions at 50 and 200 cm depths varied among study plots (Fig. 4.2). The concentrations in the control plots in each site (WKSF and RSh) did not significantly differ from those of the oil palm plots within the same study site. In West Kalimantan, WK2 had the highest concentration of Ca^{2+}, Mg^{2+}, and K^+, which was probably because WK2 was in the lowest area, thus, ions may have flowed into the plot with excess water from surrounding areas. The high $SO_{4-200cm}$ levels in WK2 may be due to the old marine sediment in the plot. In Riau, R3 had high Mg_{200cm}, K_{200cm}, and $SO_{4-200cm}$ concentration, which may have been from the bottom mineral layer, because R3 had the thinnest peat of all the plots.

4.3.3. Rainfall fluctuation

Rainfall was much higher in West Kalimantan (3,690 mm) than in Riau (2,080 mm) in the period of September 2015 to October 2016 (Fig. 4.3). From September to October 2015, rainfall was very low and an extreme drought, caused by El Niño, was experienced (Field et al. 2016; Parker et al. 2016). Rainfall at the end of October 2015 signified the commencement of the wet season in both study sites.

4.3.4. Water table fluctuation

During El Niño, the water table dropped to below 150 cm in all the plots (Fig. 4.4). During the wet season, water table levels in the oil palm plantation plots rose and were maintained at 30–50 cm in West Kalimantan and 50–70 cm in Riau.

The WKSF plot did not have a drainage channel, and its floor had been submerged since the end of April 2016. Soil solution samples at 50 cm depths in Riau could not be collected because the water table level was below 50 cm most of the time.

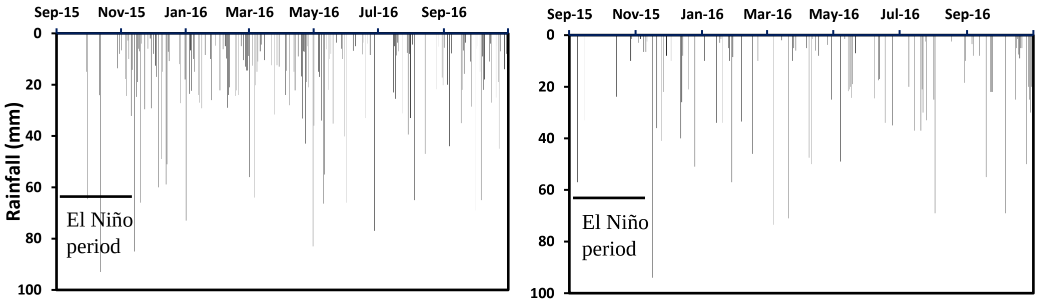

Figure 4. 3. Daily rainfall (mm) in West Kalimantan (left) and Riau (right) from September 2015 to October 2016. El Niño occurred during September–October 2015.

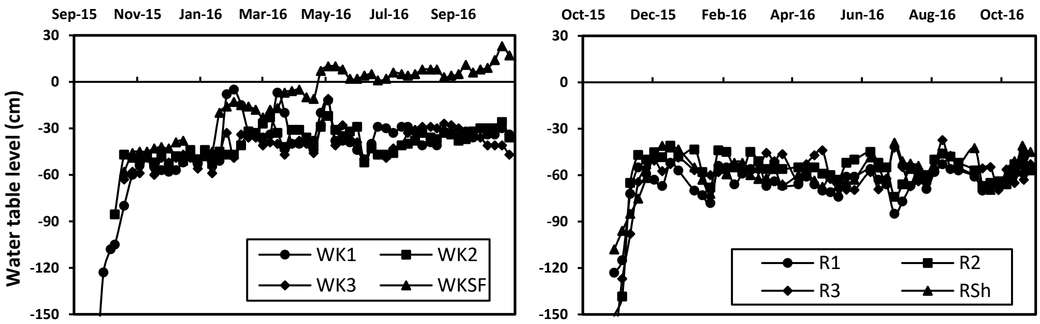

Figure 4. 4. The depth of the water table in West Kalimantan (left) and Riau (right).

4.3.5. Temporal fluctuations in soil solution composition

The start of this study coincided with an El Niño event; thus, soil solution samples at 50 cm depths had low pH and high cation (Ca^{2+}) and anion (NO_3^- and SO_4^{2-}) concentrations in West Kalimantan (Fig. 4.5). The concentrations of the other cations (Mg^{2+}, Na^+, and K^+) were also high (data is not shown). In Riau, soil solution compositions at 50 cm depth were undetermined because samples could not be collected. Soil solutions at 200 cm depths in West Kalimantan and Riau had high pH levels and cation concentrations.

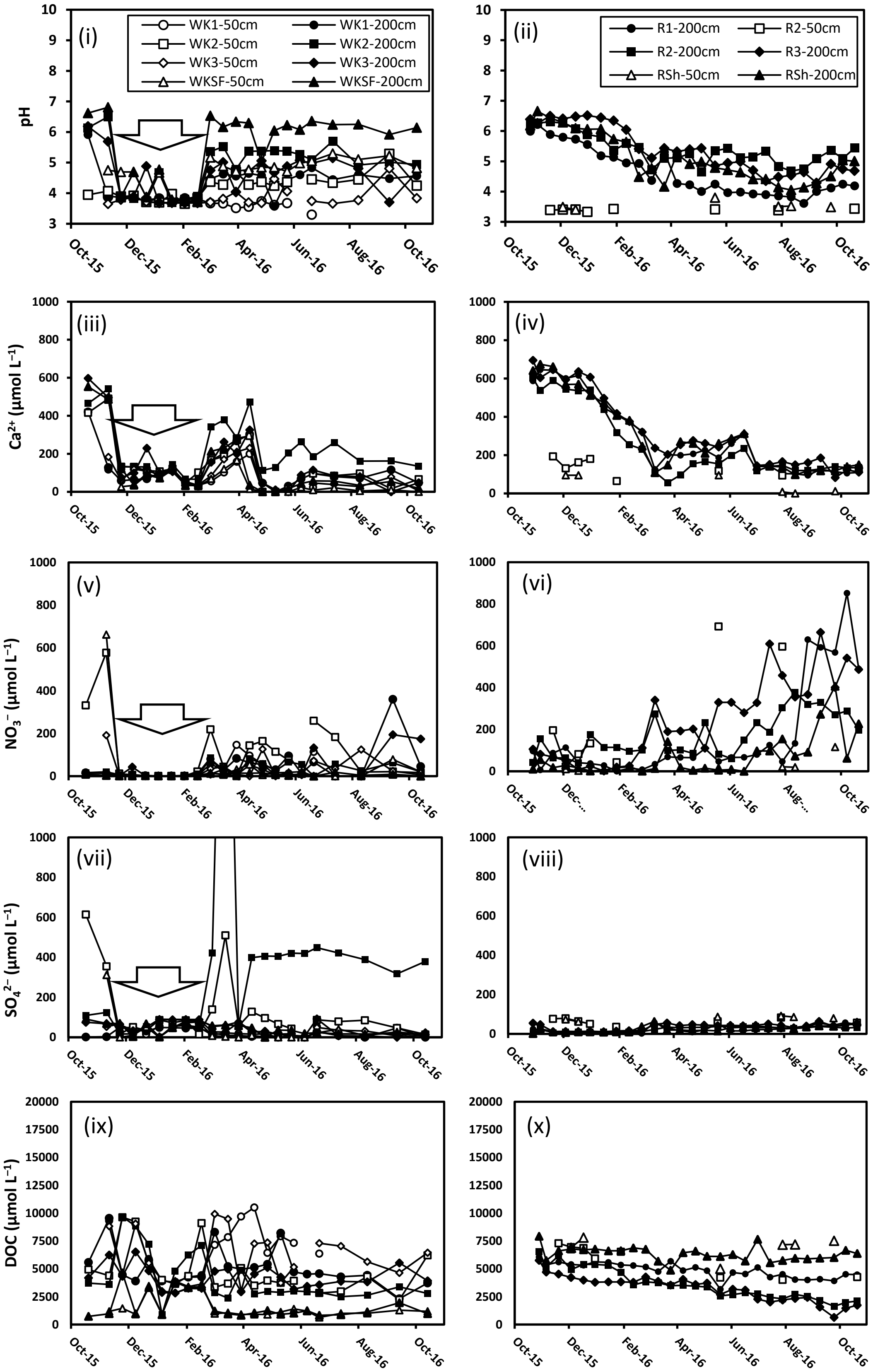

Figure 4. 5. Fluctuations in pH (i, ii), Ca^{2+} (iii, iv), NO_3^- (v, vi), SO_4^{2-} (vii, viii), and DOC (ix, x) in the soil solution in West Kalimantan (left) and Riau (right). Arrows show sharp decreases in soil solution concentrations.

After several days of rainfall in November 2015, pH and ionic concentrations dropped dramatically in West Kalimantan and remained low for three months (Fig. 4.5). The DOC concentration also sharply decreased after several weeks of rainfall. In contrast, pH levels, DOC, Ca_{200cm}, and $NO_{3–200cm}$ concentrations decreased gradually in Riau.

DOC and NO_3^- concentrations in oil palm plots in West Kalimantan sharply increased in March 2016 and stabilized after that (Fig. 4.5). At the same time, Ca^{2+} increased over the next two months and then decreased again in April 2016. In Riau, Ca_{200cm} decreased gradually over 5 months from October 2015 to March 2016 then slightly increased from April to June 2016. Afterwards, Ca^{2+} concentrations stabilized until the end of sampling.

4.4. Discussion

4.4.1. Soil solution composition at different sites and sampling depths

The concentrations of divalent cations (Ca^{2+} and Mg^{2+}) in the soil solution may reflect the solid soil composition. The concentrations of total Ca and Mg of solid soil (Table 4.1) showed similar order as those in soil solutions from 200 cm depths (Fig. 4.1a). It indicates that Ca^{2+} and Mg^{2+} could be retained by organic materials of peat. In contrast, concentrations of the monovalent cations (Na^+ and K^+) in soil solution might be determined by a different factor because of their higher mobility. Mouvenchery et al. (2013) also reported a relationship between base cations in solid soil and soil solutions in temperate peatlands composed of sapric materials. The timing of land conversions from forests to oil palm plantation would cause the differences of cation concentrations between West Kalimantan and Riau. The land was converted in 2009 and 2002 in West Kalimantan and Riau, respectively. Monovalent cations (K^+ and Na^+) are leached more easily than divalent cations (Ca^{2+} and Mg^{2+}), in accordance to this, the soil solution in Riau had lower K^+ and Na^+ concentrations. The higher Ca^{2+} and Mg^{2+} contents of the soil and soil solution in Riau would be due to condensation during the decomposition of organic matter. Furthermore, peatland types between West Kalimantan and Riau would cause the differences of cation concentrations. West Kalimantan site is the high inland type which marginally developed depend on rainfall and internal source of mineral and plants, while basin peatland type in Riau site influenced by tides. Concentrations of Ca^{2+}, Mg^{2+}, and K^{+} in soil solutions collected in this study were comparable to those of other studies on tropical peatlands (Miyamoto et al. 2009; Kawahigashi et al. 2003; Funakawa et al. 1996). However, the Na^{+} concentrations found were lower in this study than in previous studies, probably because of the long distance of our sites from the sea.

The higher water table levels and rainfall in West Kalimantan would lowered the NO_3^- concentration (Fig. 4.1a). Owing to the higher water table levels, organic matter was less oxidized in West Kalimantan than in Riau. Moreover, because of the high mobility of NO_3^-, it would be lost with water flow under the high rainfall conditions in West Kalimantan.

The higher decomposition rate of organic matter in the oil palm plantations was evident in the DOC concentrations. The secondary forest in West Kalimantan had a lower DOC (Fig. 4.2) than the oil palm plots. The dense canopy and waterlogged conditions during the wet season inhibited microbial activity to decompose organic matter resulting in a low DOC and high pH. Moore et al. (2013) found that DOC from undisturbed tropical peatland would be come only from recent plant production, while the DOC from disturbed peatland would be come from older peat in deep. In addition, land use type affects the rate of organic matter decomposition in temperate peatlands, as farmlands, which are treated with fertilizers, have a higher decomposition rate than natural vegetation untouched by fertilizers (Schwalm and Zeitz 2015). Studies on greenhouse gas emission in tropical peatland also indicate that farmland has higher decomposition rate than forest (Ishikura et al. 2017; Arai et al. 2014; Couwenberg et al. 2010; Furukawa et al. 2005). However, the land use type had no effect on peat decomposition in Riau, though the free fertilizer usage and the denser canopy and thicker litterfall, which would lead to a lower temperature (Jauhiainen et al. 2014), in RSh should result in the lower DOC than oil palm plot. This would be because RSh had a water table level similar to that of the oil palm plots (Fig. 4.4), thus, organic matter decomposition in this plot was enhanced. Furthermore, RSh was in close proximity to the oil palm plantations, and the soil solution may have been contaminated with that of the surrounding plantation.

The oxidizing condition at 50 cm depths was reflected in the soil solution composition (Fig. 4.1b). Lower pH_{50cm} and higher DOC_{50cm} and $NO_{3–50cm}$ concentrations (Fig. 4.1b) than those at 200 cm depths were observed. These findings would have been caused by oxidizing reactions in the upper layer. The soil solution from the upper layer of the 50 cm depth had more contact with the ambient environment, including atmospheric oxygen, than the deep 200 cm layer, resulting in oxidative reactions (Fenner and Freeman 2011; Bougon et al. 2011; Adamson et al. 2001; van Bremen et al. 1983).

4.4.2. Effects of drought, rewetting, and water table movement on soil solution composition

Chemical composition of soil solution during drought

Drought induced oxidative reactions that acidified the aerobic layer at 50 cm. During the drought, which occurred at the beginning of this study, the low pH_{50cm} in West Kalimantan (3.7–4.0) was caused by oxidative reactions resulting in the generation of organic acids, NO_3^-, and SO_4^{2-} (Cusell et al. 2013; Bougon et al. 2011; Loeb et al. 2008; Eimers et al. 2007; Adamson et al. 2001; van Bremen et al. 1983). In Fig. 4.5 (v and vii), the concentrations of NO_3^- and SO_4^{2-} at 50 cm were higher than at 200 cm depths. Organic C, N, and S were oxidized to organic acids, NO_3^-, and SO_4^{2-}, respectively, releasing H^+ into the soil solution. These oxidative reactions might have also occurred in Riau, although the evidence was unavailable due to the absence of soil solution samples at 50 cm.

In contrast, during the drought, reduction reactions occurred in the 200 cm anaerobic layer. The pH_{200cm} was higher (5.9–6.8) than the pH_{50cm}, probably due to reduction reactions, such as denitrification and sulfate reduction, which consumed H^+ (Cusell et al. 2015; Adamson et al. 2001; van Bremen et al. 1983). Low concentrations of $NO_{3–200cm}$ and $SO_{4–200cm}$ during the drought may have also been because of these reactions (Fig. 4.5, i–ii, v–viii). The soil solutions at 50 cm depths were more acidic than at 200 cm because the limited downward movement of water prevented the acidification of the deeper layers.

The drought induced high cation concentrations in both the aerobic and the anaerobic layers. Ca^{2+} at both layers in West Kalimantan and Riau were higher during the drought than during wet season (Fig. 4.5, iii, iv). High cation concentrations during this period were due to the limited movement of water. An increase in base cation concentrations followed by increasing pH in an anaerobic environment has also been previously reported in temperate peatlands (Cusell et al. 2015; Loeb et al. 2008; Adamson et al. 2001).

Rewetting peatlands

A sharp decline in pH and the concentrations of Ca^{2+}, NO_3^-, and SO_4^{2-} occurred in West Kalimantan in November 2015 was caused by rainfall which include several processes of dilution, transportation, and flowage (Fig. 4.5, i and iii). The rewetting process resulted in acid transportation from the upper acidified layers to 200 cm depths. These low pH levels persisted for three months. During this period, almost one third (1,040 mm) of the total rainfall (3,270 mm) in the study period was experienced and contributed to the acidification at 200 cm depths. Moreover, the low concentration of $NO_{3\text{–}50cm}$ (Fig. 4.5, v and vii) during these three months was supported by strongly acidic conditions, which inhibited nitrification, similar to the findings of previous studies on peat (Bazin et al. 1991) and mineral soils (Kyveryga et al. 2004; Ste-Marie and Paré 1999). Furthermore, the low concentration of these anions in the deeper layer indicated the continuation of denitrification and sulfate reduction processes.

However, the huge acid transportation did not occur in Riau probably because of the lower levels of precipitation. pH_{200cm} and Ca_{200cm} in Riau decreased gradually (Fig. 4.5, ii and iv). High Ca^{2+} concentrations in both the solid soil and soil solutions from Riau (Table 4.1, Fig. 4.1a) were considered to act as a pH buffer.

Effects of the increased water table level and lower rainfall intensity

The increased moisture supply from the raised water table would stimulate microbial activity and increase the chemical components in soil solution. The increased $NO_{3\text{–}50cm}$, Ca_{50cm}, and DOC_{50cm} concentrations in West Kalimantan (Fig. 4.5) in early March 2016 were likely because of the enhanced microbial activity caused by the increased moisture content (Fig. 4.4). The reduced rainfall intensity

(Fig. 4.3) also supported these increases. The water table level in West Kalimantan increased in January 2016 (Fig. 4.4), four weeks before the increases NO_{3-50cm}, Ca_{50cm}, and DOC_{50cm} concentrations. Probably, favoring microbial activity from raised water table takes time. This delayed response has also been observed in temperate peatlands (Mettrop et al. 2015; Clark et al. 2005; Adamson et al. 2001). Water table levels in Riau were well maintained at 50–70 cm (Fig. 4.4) during this study; therefore, no effect on increased ionic concentration was detected.

Oxidizing conditions and microbial activity enhanced by the moisture supply from the elevated water table resulted in high NO_{3-50cm} concentrations. Increased $NO_{3-200cm}$ (Fig. 4.5, v) were caused by NO_3^- transportation from the upper layers, although this could not be confirmed in Riau due to insufficient soil solution samples from the 50 cm depths.

4.4.3. Effects of fertilizer

The contribution of fertilizers to the chemical composition of the soil solution was unclear, despite our considerations of the type, quantity, and time of fertilizer applications in each oil palm plantation plot, although these data are not included in this paper. The increases in ionic concentrations were unsynchronized with fertilizer application. Furthermore, fluctuations in chemical compositions of soil solution in oil palm plantation plots and the secondary forest were similar in West Kalimantan. High plant uptake and bonding to organic matter (Chapin et al. 2003) may be partly attributed to the use of fertilizers. Drought, rewetting, and water table movement in tropical peatlands, however, would have more influence on the fluctuations of ionic concentrations.

4.4.4. Suggestion for sustainable management of peatland

We found that the chemical composition of the soil solution of tropical peatlands easily changes. Thus, the cultivation of peatlands should be conducted under very careful management. A high water table level during the dry season is necessary to increase the benefit of high water nutrient content to crops, reduce excessive acid production by oxidization of peat, and prevent fires. Reducing evapotranspiration and water recharge into farmlands might be a reasonable way to keep the water table in a high level. Excess water during the wet season should be collected in a reservoir, regardless of cost, to avoid eutrophication in downstream.

4.5. Conclusion

The peat decomposition in subsoil through chemical composition of soil solutions in tropical peatlands was investigated. The factors affecting soil solution composition in the studied peatlands were solid peat properties, age of land cultivation, sampling depth, and land use type (secondary forest and oil palm plantation). Moreover, the factors controlling the fluctuations in soil solution composition were seasonal variations (drought and wet) and water table movement. Drought induced oxidative reaction such as the generation of organic, nitric, and sulfuric acids in the aerobic layer. Basic cation concentrations in the anaerobic layer increased during the drought due to organic matter decomposition and the limited downward movement of water. Rewetting of the peatland by the rainfall caused acidification in the deeper layers because of acid transportation from the upper acidified layer. Increased water table levels and simultaneous water supply enhanced microbial activity and resulted in increased ionic concentrations. Thus, water management to increase the water table level during dry season and to collect the excess water into a reservoir during wet season is the key factor for managing tropical peatland with regard to nutrient supply for oil palm and environmental sustainability.

Chapter 5. General discussion

5.1. Subsoil acts as the active layer of peat decomposition in mature oil palm plantation.

In a peat profile under mature oil palm plantation (14 years old) in Sumatra, the active decomposition layer was shifted downward to subsoil. The CO_2 efflux from the peat surface was not correlated with environmental factors including peat temperature, moisture, and water table level. The CO_2 efflux was more closely synchronized with the fluctuation of CO_2-EP in the subsoil, suggesting that the contemporary CO_2 efflux could be derived from CO_2-EP. This result implies that a longer cultivation period of mature oil palm plantation affected the higher loss of labile fractions in the topsoil and peat becomes more recalcitrant. Thus, the CO_2 released from the peat surface may reflect the moisture condition of subsoils, suggesting that appropriate water table management is important for minimizing further decomposition of peat materials in deeper soil layers. The subsoil of cultivated peatland is considered to be vulnerable, and its exploitation should be avoided.

5.2. Seasonal fluctuation of peat decomposition in the subsoil

Seasonal fluctuation of peat decomposition in subsoil was observed through soil solution study in tropical peatland of West Kalimantan and Riau across various land use (oil palm plantation, forest, and shrub). During the drought, the pH_{50cm} was low (3.7–4.0), which was influenced by oxidation reactions such as organic acids and NO_3^- generations. Meanwhile, the pH_{200cm} was high (5.9–6.8) due to reduction reactions such as denitrification. High cation concentrations at 50 and 200 cm depths would result from organic matter decomposition and the limited downward movement of water. At the beginning of the wet season, rewetting the West Kalimantan peatland caused a sharp decrease in pH and ionic concentrations at 50 and 200 cm depths because of the transportation of ions from the upper acidified layer. This low pH and ionic concentration were persisted for three months. However, rewetting in Riau resulted in a gradual decrease of pH and Ca^{2+} concentration because of the lower rainfall levels than West Kalimantan. The higher pH levels and ion concentrations in West Kalimantan than in Riau would be influenced by the enhanced microbial activity due to water supply from the risen water table in this site. This study showed that the seasonal rainfall and water table movement were the main factors controlling the soil solution composition in the subsoil.

5.3. Evaluation of CO_2 production and nutrient release into the subsoil

A sampling plot for CO_2 production study is close to the plots used to soil solution study, which approximately 1, 1, 2, and 3 km distance from R1, R2, R3, and RSh plot, respectively. CO_2 measurements were conducted 12 sampling times from February to October 2016, which fitted with soil solution samplings. Spearman's rank order analysis was used to find a correlation between CO_2-EP at 50 cm depth (CO_2-EP_{50cm}) with several soil solution properties in different depths such as Ca_{200cm}, pH_{200cm}, $NO_{3\text{–}200cm}$, and $NH_{4\text{–}200cm}$. Due to the limited number of soil solution samples collected from 50 cm depth, I only use soil solution data from 200 cm depth for this analysis.

The result shows that CO_2-EP_{50cm} had a significant positive correlation with Ca_{200cm} ($p < 0.05$) at all sampling sites in Riau (Fig. 5.1). The increased CO_2-EP_{50cm} is followed by increasing Ca_{200cm}, suggesting that the peat decomposition at 50 cm depth released both CO_2 and Ca^{2+}. CO_2-EP_{50cm} was released to the atmosphere while Ca^{2+} was transported into 200 cm depth by percolation water, which subsequently increased the concentration of Ca_{200cm}.

However, CO_2-EP_{50cm} had no correlation with pH_{200cm} (Table 5.1) possibly because H^+ in 200 cm layer was consumed during reduction reaction such as denitrification. H^+ was derived from nitrogen (N) mineralization and subsequent nitrification in 50 cm depth, (Cusell et al. 2015; Adamson et al. 2001; Liu et al., 2010). CO_2-EP_{50cm} had no correlation with $NH_{4\text{–}200cm}$ and $NO_{3\text{–}200cm}$ possibly because of the N transformation process and plant uptake. Mineralization of organic N in 50 cm depth releases NH_4^+, which is subsequently transformed to NO_3^- by microbial nitrification under aerobic condition. Then the plant root uptake reduces the concentration of NO_3^- in soil solution (Aslam et al., 1995). Due to the N transformation and plant uptake, the remain NO_3^- and NH_4^+ transported into 200 cm depth would unsynchronized with the increasing CO_2-EP_{50cm}. Moreover, $NO_{3\text{–}200cm}$ would reduce by the further N transformation of denitrification (Nie et al., 2015).

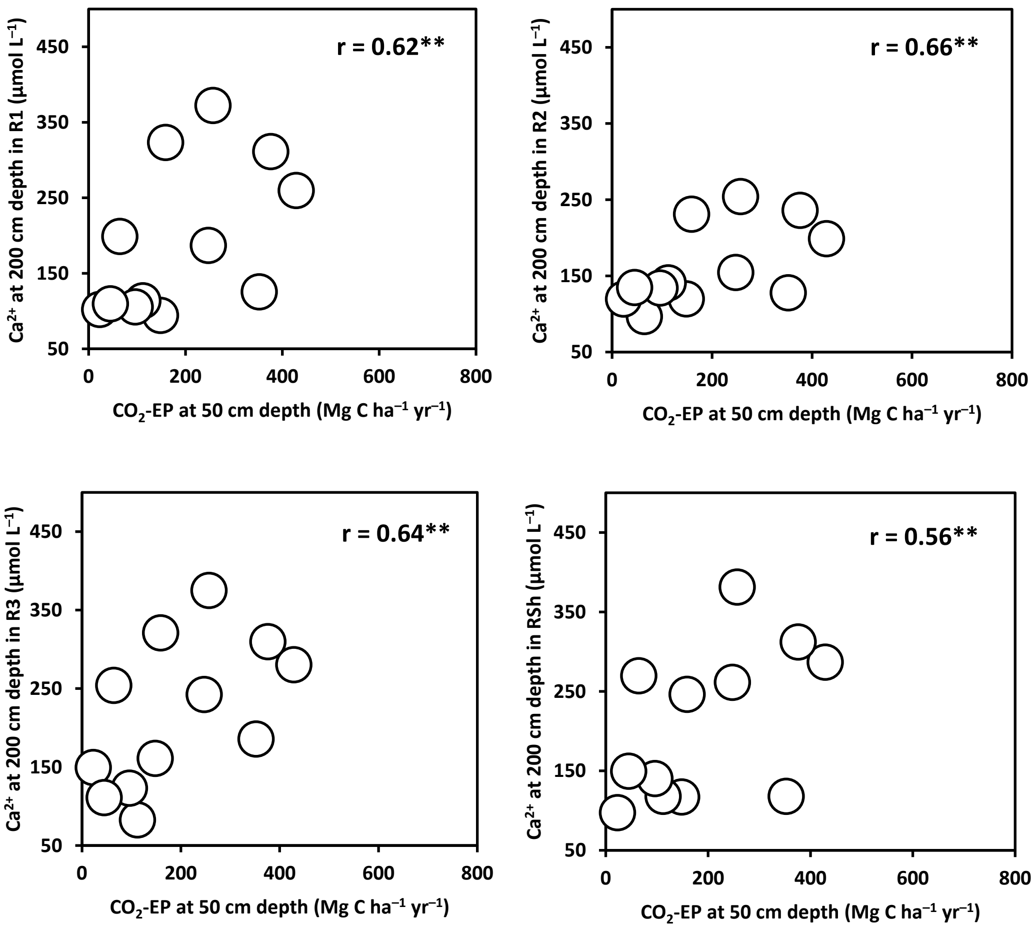

Figure 5. 1. Correlation between Ca_{200cm} in 4 study sites and CO_2-EP at 50 cm in Riau (n = 12). Asterisks (**) indicate significant level at $p < 0.05$.

Ca_{200cm} had a strong correlation with pH_{200cm}, $NO_{3\text{–}200cm}$, and $NH_{4\text{–}200cm}$. (Table 5.1). The significant positive correlation between Ca_{200cm} and pH_{200cm} indicates that generated H^+ is mitigated by gradual release of Ca^{2+}.

Ca_{200cm} had a significant negative correlation with $NO_{3\text{–}200cm}$ and $NH_{4\text{-}200cm}$ (Table 5.1). Ca^{2+} is a substantial element for maintaining membrane selectivity of ion uptake and ion retention by plant cells (Marschner, 1995). The high Ca_{200cm} in early of this study is possibly stimulating $NO_{3\text{–}200cm}$ uptake by plant and affected the low $NO_{3\text{–}200cm}$ concentration in the soil solution. However, oil palm roots mostly grow in 0–35 cm depth of soil with only a few roots penetrating deeper than 1 m

(CABI, 2018; Jourdan and Rey 1997). Ion uptake by roots in 200 cm depth of anaerobic environment is rare because of the low oxygen concentration (Drew and Lynch, 1980), although a few oil palm roots seem adaptable in such condition (Veloo et al., 2015).

Table 5. 1. Matrix correlation between CO_2-EP at 50 cm depth and soil solution composition of Ca_{200cm}, pH_{200cm}, $NO_{3-200cm}$, and $NH_{4-200cm}$ in each study sites.

Properties	Sites	CO_2-EP_{50cm} (Mg C ha^{-1} yr^{-1})	Ca_{200cm} (µmol L^{-1})	pH_{200cm}	$NO_{3-200cm}$ (µmol L^{-1})
pH_{200cm}	R1	-0.04	0.59**		
	R2	0.29	0.78***		
	R3	0.31	0.71**		
	RSh	0.01	0.71**		
$NO_{3-200cm}$	R1	-0.27	–0.81***	–0.59**	
(µmol L^{-1})	R2	-0.50	–0.66**	–0.76***	
	R3	-0.24	–0.83***	–0.85***	
	RSh	-0.43	–0.70**	–0.24	
$NH_{4-200cm}$	R1	-0.51*	–0.78***	–0.23	0.79***
(µmol L^{-1})	R2	-0.52*	–0.59**	–0.41	0.68**
	R3	-0.12	–0.71***	–0.61**	0.88***
	RSh	-0.40	–0.58**	–0.15	0.74***

Asterisk (*) indicates significant level at $p < 0.10$, (**) at $p < 0.05$, while (***) at $p < 0.01$

The more plausible explanation of the negative correlation between Ca_{200cm} and $NO_{3-200cm}$ is the increased nitrification during the wet season which releasing H^+ in 200 cm depth and subsequently mitigated by Ca_{200cm}. During El Niño, the dried peat induced reduction reaction in an anaerobic layer which increased Ca_{200cm} (Fig. 4.5. iv). On the other hand, the very dried peat in the aerobic layer may reduce the activity of microbial decomposer and result in the low Ca_{50cm} and NO_{3-50cm}. The low downward movement of water caused Ca_{200cm} and $NO_{3-200cm}$ remain low. After the increased soil moisture during the rewetting period, nitrification in the aerobic layer was increased and NO_3^- transported into 200 cm depth by diffusion and percolation water. The increased N mineralization during wet season was also evidence in $NH_{4-200cm}$ (Fig. A.1). In September 2016, the concentration of $NO_{3-200cm}$ and $NH_{4-200cm}$ extremely increase, indicating the optimum peat moisture condition to the activity of microbial decomposer was reached. In October 2016, the concentration of $NO_{3-200cm}$ and $NH_{4-200cm}$ were then slightly decreased due to the high amount of rainfall, indicating the water saturation suppressed the peat decomposition. During nitrification, the transported H^+ into 200 cm depth was mitigated by Ca_{200cm}, resulted in the lowering concentration of Ca_{200cm}.

5.4. Conclusion

The active layer of peat decomposition in mature oil palm plantation was shifted downward to subsoil. Peat decomposition in subsoil seasonally fluctuates, where the rainfall and water table movement were dominant factors affecting the fluctuation. Peat decomposition in subsoil released CO_2 to the atmosphere, while mineral nutrients of Ca^{2+}, NO_3^-, and NH_4^+ transported to the 200 cm depth. However, no correlation between CO_2-EP_{50cm} and pH_{200cm}, $NO_{3-200cm}$, and $NH_{4-200cm}$ is possibly due to the complex reaction in 200 cm depth such as pH buffer and denitrification. The increasing peat decomposition in the moist condition of peat during wet season affects the increasing $NO_{3-200cm}$, and $NH_{4-200cm}$. The decreased Ca_{200cm} during wet season caused by the increased H^+. This study emphasized the importance of the high water table level treatment in peatland under the mature oil palm plantation, in order to suppress the peat decomposition in the subsoil. Moreover, the subsoil is vulnerable to decompose, thereby prohibited to exploit.

Chapter 6. Conclusion

Development of oil palm plantation in Indonesia increases the rural prosperity and the national economic growth as well. However, the rapid expansion of oil palm plantation in peatlands accelerates organic matter decomposition, which releases CO_2 gas and mineral nutrient, and leads environmental degradation. A better understanding of peat decomposition characteristic is important to plan mitigation action regarding the expansion of oil palm plantation in tropical peatland. This study was aimed to evaluate the peat decomposition characteristic based on CO_2 efflux and nutrient release in Riau and West Kalimantan, Indonesia.

A huge amount of CO_2 gas was released into the atmosphere once natural peatland converted into oil palm plantation. After 14 years cultivation, CO_2 efflux was not controlled anymore by environmental factors such as water table level, soil temperature, and moisture. The advanced peat decomposition reduces the labile fraction of organic matter at topsoil layer and peat goes to recalcitrant. Nowadays, subsoil acts as the active layer of peat decomposition and mainly contributes to the measured CO_2 efflux from peat surface. The fluctuation of CO_2 efflux is the reflection of soil moisture condition in the subsoil. Considering the vulnerability of subsoil to the decomposition process, hence, the exploitation of subsoil into aerobic condition is prohibited.

Peat decomposition in subsoil seasonally fluctuated. During the dry season, the oxidative reactions occurred in the aerobic layer and nitric, sulfuric, and organic acids were generated. While the concentrations of basic cations in the anaerobic layer were increased due to organic matter decomposition and the limited downward movement of water. In the wet season, the high rainfall in West Kalimantan caused rapid acidification in the deeper layers due to acid transportation from the upper acidified layers. Increased water table levels and simultaneous water supply enhanced microbial activity and resulted in increased ionic concentrations. The lower rainfall in Riau than West Kalimantan caused a gradual change of ionic concentrations of soil solution in the deeper layers.

Peat decomposition process in subsoil was evidenced in both CO_2 and soil solution composition study. The CO_2 released into the atmosphere is synchronous with the released mineral nutrients to the soil solution. However, NH_4^+ and NO_3^- were unsynchronized with the CO_2 release due to the complex mechanism of plant root uptake and N transformation.

Based on the characteristics of peat decomposition under oil palm plantation, peat at water saturated condition would suppress CO_2 production and mineralization of organic matter. Mitigation of C and nutrient loss in oil palm plantation can be conducted by managing the water table at a high level, even in dry season, though CO_2 emission and nutrient loss still occur. During the wet season, the reservoir can be used for collecting the excess water. Thus, water management is the key factor for managing tropical peatland with regard to oil palm productivity and environmental sustainability.

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Appendix

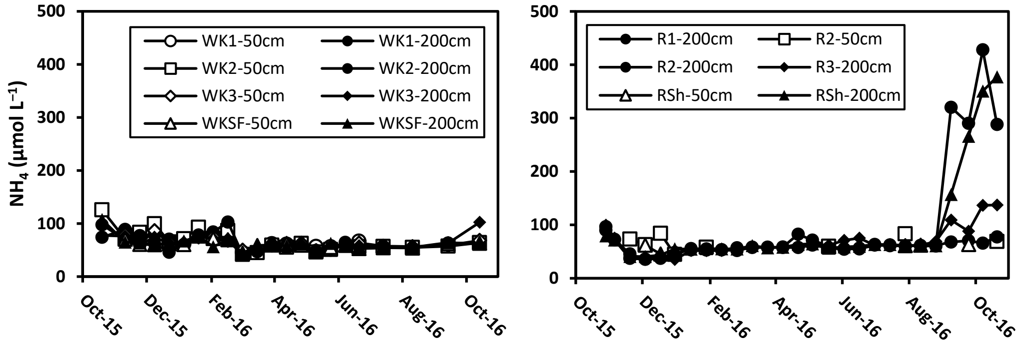

Figure A. 1. Fluctuations in NH_4^+ in the soil solution in West Kalimantan (left) and Riau (right)

Publication

Chapter 4

Marwanto S, Watanabe T, Iskandar W, Sabiham S, Funakawa S, 2018. Effects of seasonal rainfall and water table movement on the soil solution composition of tropical peatland, Soil Sci. Plant Nutr. doi: 10.1080/00380768.2018.1436940.