Effects of long-term nitrogen fertilization on soil CO_2 and N_2O fluxes in a tropical peatland

（熱帯泥炭地における長期窒素施肥が土壌CO_2およびN_2Oフラックスに及ぼす影響）

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CHAPTER 1

General Introduction

Tropical peat is an accumulation of partially decayed organic matter which has been formed over thousands of years in waterlogged environments that lack oxygen (Jaenicke et al., 2010). The decomposition of organic matter decreases in the presence of water and absence of oxygen whereas peat is formed when the rate of accumulation exceeds the rate of decomposition. The incomplete decomposition of dead tree material, especially roots, has led to the slow but progressive accumulation of partially decomposed organic material (peat) over millennia and has given this ecosystem a very high carbon density, with typical values in the range of 100-250 t C ha^{-1} (Murdiyarso et al., 2010; Page et al., 2011).

The world's largest area of tropical peatland ecosystems is found in South-East Asia with 56 % of the former and 77 % of the latter owing to the large extent of peatlands and the considerable thickness of peat (regularly exceeding 10 m) in this region. Within Southeast-Asia, Indonesia has the largest area (206,950 km^2, 47% of total) followed by Malaysia (25,889 km^2, 6%) and Papua New Guinea (10,986 km^2, 3%) with other countries in this region containing much smaller amounts (1 % collectively in Brunei, Myanmar, the Philipines, Thailand and Vietnam) (Page and Rieley, 2016). In Malaysia, peatlands occupy an area of about 2.6 Mha of peatlands, of which about 70 % (~1.6 Mha) are in state of Sarawak (Melling, 2016). Today, tropical peat swamp forest has been developed and mostly used for agricultural activities, particularly for oil palm cultivation as oil palm plays a significant role in the Malaysia economic growth. Conversion of tropical peat land into oil palm plantations attracts global attention on greenhouse gas emissions (GHGs) such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Land management such as drainage, ground water table control, compaction and fertilization are essential to ensure suitability of the peatland for agriculture. Despite this, development of peatland for agricultural land influences GHGs emissions.

Carbon dioxide (CO_2) is the largest greenhouse gas (GHG), accounting for 60% of the total greenhouse effect (Rastogi et al., 2002). The Intergovernmental Panel on Climatic Change (IPCC, 2007) reported that the global atmospheric concentration of CO_2 has increased from a pre-industrial value of about 280 to 379 ppm in 2005, exceeding the natural range over the last 650 000 year (180 to 300 ppm, as determined from ice cores), and that the annual CO_2 concentration growth rate was larger during the last 10 year (1995 to 2005 average:1.9 ppm per year). In natural condition where the water table is at or above the peat surface, decomposition of deposited organic matter takes place at a reduced rate along anaerobic pathways by methanogenic heterotrophic bacteria, resulting in the release of CH_4. Drainage and controlling of groundwater level create oxic condition in peat profile and accelerate the rate of peat decomposition and mineralization, which enhance soil carbon dioxide (CO_2) (Van Huissteden et al., 2006; Hooijer et al., 2010; Page et al., 2011) but decreased CH_4 emissions. Addition of fertilizer to promote palm productivity is likely to foster peat mineralization and stimulate soil CO_2 emissions (Hergoualc'h and Verchot 2014, Comeau et al., 2016).

N_2O gas is chemically stable, with its half-life period of 114 years, and therefore this stability led to 265-fold higher greenhouse effect than CO_2 (IPCC, 2013). Providing other conditions allow, maximum N_2O emissions from peat usually occur under conditions intermediate between aerobic and anaerobic; changes in peat hydrology may therefore have a major influence on N_2O emissions (Jauhiainen et al., 2011). As drainage increases peat mineralization rates and nitrate (NO_3^-) availability, the potential for N_2O production becomes significantly greater (Hadi et al., 2000; Jauhiainen et al., 2011). Similarly, applications of nitrogen fertilizer generally serve to increase rates of N_2O emission (Hadi et al., 2000; Takakai et al., 2006). A review by Page et al. (2011) reported that accelerated rates of nitrogen mineralization under drained aerobic conditions, together with high rates of fertilizer application, may contribute to high rates of N_2O emission in tropical peatland.

To date, few short-term studies evaluated the effect of nitrogen (N) fertilizer on CO_2 and N_2O and emissions in tropical peatlands. Sakata et al. (2014) and Watanabe et al (2009) found that N fertilizer had no significant effect on CO_2 emissions in young oil palm plantation and sago plantation on peat while other study observed an increase in CO_2 flux from agricultural land and a decrease from degraded land after N fertilizer application (Jauhiainen et al., 2014). No significant effect of N fertilizers on N_2O emission from tropical peatland was reported by Sakata et al. (2014) while Hadi et al. (2000) reported that the addition N fertilizer significantly reduced the emission of N_2O because of the high ammonium content that inhibited nitrification. Takakai et al. (2006) and Oktarita et al. (2017) reported that N fertilizer had no significant effect on N_2O emissions was due to predominantly high emissions resulting from peat decomposition. Peat decomposition was related closely with both CO_2 and NO emissions because N_2O emissions was reported to increase with the increase of CO_2 emission (Kimura et al., 2012; Mu et al., 2014). Of these studies, Oktarita et al. (2017) conducted the only long-term study. Long-term studies are needed as environmental conditions and peat characteristics with time could exhibit a different response of CO_2 and N_2O emissions to N addition. As compared to CO_2, emissions of N_2O are typically inconsistent and usually not well correlated with any single environmental factor. The understanding on the effects of N fertilizers from cultivated tropical peatland are still limited, considering its importance in developing mitigation approach for sustainable management of tropical peatland for agriculture. Moreover, finding a suitable nitrogen rate for optimum oil palm growth and yield whilst maintaining low environmental impact is also crucial for the economic growth of the oil palm sector in Malaysia. Thus, the objectives of this study were to:

1) quantify soil N_2O emissions by varying the rates of N fertilizers and the key factors influencing the response of soil N_2O emissions under N fertilization were identified.
2) quantify the annual soil CO_2 emissions from an oil palm plantation on a tropical peat soil from different N rates and to identify the regulatory factors affecting soil CO_2 fluxes over time, including temporal changes of GWL on CO_2 fluxes
3) investigate the effects of different N rates on peat decomposition under different water-filled pore space (WFPS).

This dissertation is divided into 8 chapters. Chapter 1 is the general introduction to the background and objectives of this study. Chapter 2 provides a review of the relevant literature on CO_2 and N_2O productions in soils particularly tropical peat soil. Chapter 3 describes the study sites, experimental design, treatments, soil type and the methodologies used in this study. Chapter 4 shows the results of soil N_2O emissions under different rates of N fertilizers and the key factors influencing the response of soil N_2O emissions under N fertilization (published) (Chaddy et al., 2019). Chapter 5 shows the results of the effect of long-term ground water level control and N fertilization on CO_2 fluxes from oil palm plantation on tropical peatland. Chapter 6 reports on the influence of N rates on the peat decomposition at laboratory scale under different WFPS. Chapter 7 is the general discussion on the results and the connection of each chapter of this study. Finally, the whole study is summarized in Chapter 8.

CHAPTER 2

Literature Review

2.1 Soil Greenhouse Gases (GHGs)

One-third of the greenhouse gas (GHG) emissions are produced by agriculture (Gilbert, 2012). The impact of agriculture on GHG emissions has become a key issue, especially when considering that natural carbon (C) and nitrogen (N) cycles are influenced by agricultural development. A greenhouse gas (GHG) is any gaseous compound in the atmosphere that is capable of absorbing infrared radiation, thereby trapping and holding heat in the atmosphere. By increasing the heat in the atmosphere, greenhouse gases are responsible for the greenhouse effect, which ultimately leads to global warming (Lallanilla, 2019). Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the three most important greenhouse gases (GHGs), after water vapor (Luan et al., 2019).

GHG emissions from soils need to be better quantified for global budgets, since 35% CO_2, 47% CH_4, 53% N_2O, and 21 % nitric oxide (NO) of the respective total annual emissions relate to soil degassing (IPCC, 2007). Land use and land use change have an important role in the increase of GHG emissions, where the production of this gas from soils generally respond to natural or anthropogenic processes and to specific environmental conditions. Soil CO_2 is produces in aerobic conditions, while CH_4 in soil is produce in anaerobic conditions. Soil N_2O is produce in both aerobic (nitrification) and anaerobic (denitrification) conditions (Hatano, 2019). Carbon dioxide (CO_2) is an important greenhouse gas accounting for 60 % of the total greenhouse effect (Rastogi et al., 2002). The concentration of CO_2 in the atmosphere has increased from 280 ppmv at beginning of the industrial revolution to the present-day value of 391 ppmv (WMO, 2012). Global warming potential (GWP) of CH_4 and N_2O is 28 and 265 times larger than CO_2, respectively, over a

100-year period, and those GWP values do not include climate-carbon feedbacks (IPCC, 2014). Cultivated soils produce more than 50% of all anthropogenic N_2O emissions (Smith et al., 2007; Robertson, 2014).

2.2 Tropical Peatland and Soil GHGs emissions

Peat soil contains approximately 15 to 25% of the terrestrial soil C and N worldwide (Batjes, 1996; Hatano, 2019). One-third of the C stored in peatlands (191 Pg) is located in the tropics (Page and Rieley, 1998). Thus, tropical peatlands have important implications for climate change and greenhouse gas emissions because they are globally important terrestrial C and N pools. Murdiyarso et al. (2010) reported that forested tropical peatlands in Southeast Asia are rapidly being converted into production systems by introducing perennial crops for lucrative agribusiness, such as oil-palm and pulpwood plantations, causing large GHG emissions. In drained peatlands, CO_2 contribute 98% or more of the total combined global warming potential (GWP) of CO_2, CH_4 and N_2O (Couwenberg et al., 2010; Jauhiainen et al., 2011). Because drainage of peatlands generally lowers CH_4 emissions (Martikainen et al., 1992; Flessa et al., 1998), additional anthropogenic emissions are assumed to be insignificant in drained peatlands (Murdiyarso et al., 2010). Drainage in peat increases peat mineralization rates and NO_3- availability, which resulted in significantly greater N_2O production as reported by Hadi et al. (2000) and Jauhiainen et al. (2011). Applications of N fertilizer for crop production generally serve to increase rates of N_2O emission (Sakata et al., 2014; Hadi et al., 2000; Takakai et al., 2006).

2.3 Production of soil CO_2 in Soil

Total soil carbon dioxide (CO_2) efflux is a combination of plant-root, heterotrophic and mycorrhizal respiration (Kuzyakov, 2006). Root respiration contributes on average up to

~50% of the total soil respiration, yet may vary between 10 and 95% subject to season and vegetation type (Hanson et al., 2000). The tropical peatland carbon and GHG balance is determined largely by the net balance between carbon uptake in photosynthesis and carbon release through ecosystem respiration by: (a) vegetation (referred to as autotrophic respiration and resulting in CO_2 emissions from both plant foliage and root systems) and (b) by the organisms involved in organic matter biological decomposition (known as heterotrophic respiration, involving the loss of carbon as CO_2 and CH_4 by organisms involved in aerobic and anaerobic decomposition of organic matter, comprising plant litter, roots and their exudates, dead animals, fungi, bacteria and the peat itself (Page et al., 2011).

2.3.1 Factors Influencing Soil CO_2 Emission

2.3.1.1 Soil Moisture and Ground Water Level (GWL)

Soil moisture is the single most important soil parameter for soil gas emissions, since it controls microbial activity and all related processes. Drainage and compaction increased the bulk density of peat, leading to a decrease in macropores (>600µm) and an increase in micropores (3–30 µm), resulting in increased water retention capacity and unsaturated hydraulic conductivity (Kasimir-Klemedtsson et al.,1997; Silins and Rothwell, 1998). Melling et al. (2005) had shown that water-filled pore space (WFPS) had become the dominant factor in affecting soil CO_2 emission in an oil palm plantation on tropical peatland with the highest CO_2 flux occurred at WFPS between 45 and 57%. Soil respiration attained a maximum at about 60% WFPS decreasing afterwards (Aon et al., 2001). WFPS strongly influenced the rate of soil gas exchange with the lowest gas exchange were measured in the range 10 to 30% WFPS (Aon et al., 2001). Higher bulk density and WFPS of compacted soil, which very likely reduced aeration and restricted gas diffusivity creating anoxic conditions that limited aerobic respiration, thereby lowering CO_2 production (Ball et al., 2008; Beare et al., 2009). The relative rates of respiration (O_2 uptake and CO_2 production) increase linearly with increasing soil water content to a maximum at 60% WFP and decrease thereafter. Below 60% WFPS, water limits microbial activity, but above 60%, aerobic microbial activity decreases-apparently the result of reduced aeration (Linn and Doran, 1984). Increases in both soil moisture and soil temperature led to increase in soil CO_2 emission (Wilson and Al-Kaisi, 2008) while an increase of soil respiration with decreasing temperature was found in higher soil moisture content (Kechavarzi et al., 2010). Low volumetric water content (<10%) strongly limited the response of soil respiration to soil temperature, indicating that relationship between soil CO_2 fluxes and soil temperature was strongly modulated by soil moisture (Almagro et al., 2009). Fang and Moncrieff (2001) reported that the soil moisture content may affect the magnitude of soil respiration as well as its response to temperature due to the interaction between moisture and temperature. The gravimetric water content of 30% was obviously too dry for microorganisms, leading to higher CO_2 emission rates of 0–2 mm surface soils at 70% gravimetric water content (Kimura et al., 2012). Ruser et al. (2006) found soil respiration was significantly reduced at soil moisture level (98% WFPS) of the tractor-compacted soil (Ruser et al., 2006).

Undrained peat deposits consist of plant remains (about 10% by weight of peat) and water (90%), accumulated in waterlogged and usually acidic conditions over thousands of years (Hooijer et al., 2010). However, conversion of tropical peatland to agricultural land required drainage and lowering of ground water level to provide suitable soil for the crops to grow. The exposure of previously saturated peat to aerobic conditions had been reported to increase massive soil CO_2 emission (Page et al., 2011; van Huissteden et al., 2006; Hooijer et al., 2010). If the water table is at or above the peat surface, then aerobic peat decomposition is in practice prevented and decomposition of deposited organic matter takes place at a reduced rate along anaerobic pathways by methanogenic heterotrophic bacteria, resulting in the release of CH_4 (Page et al., 2011). The higher heterotrophic respiration from the−50 cm water table treatment indicates that a statistically significant portion of microbial decomposition occurred in the zone between −30 cm and−50 cm, indicating that the organic matter from the soil layers to a depth of−50 cm are still relatively easy to decompose, and can result in a significant contribution to the overall carbon loss of fenland agricultural peat (Matysek et al., 2019). Raising the water table from−50 cm to −30 cm would decrease the rate of peat mineralisation to CO_2 by 31% in fenland agricultural peat (Matysek et al., 2019). Peat decomposition at undrained peat swamp forest increased with decreasing GWL and peaked at a GWL between −0.6 and −0.9 m (Itoh et al., 2017). Peat at undisturbed peatland, with a lower bulk density and greater porosity, probably contributed to high water permeability and gas transport (oxygen and CO_2) under low-GWL conditions, resulting in the greater correlation between peat decomposition and GWL (Itoh et al., 2017). Groundwater levels corresponding to potential water capillarity that affects moisture conditions of top layer of peat soil. Rise of capillary water in peat soil reached a maximum height of 50 cm which was characterized by the increase in volumetric water content at the top layer in the range of 105–127% at bulk density of 0.1 g cm^{-3} and 141–181% at bulk density 0.2 g cm^{-3}. The highest value of water content (308%) was achieved in the treatment of GWL at 40 cm below peat surface with bulk density at 0.2 g cm^{-3} and the lowest (37%) was in the treatment of GWL at 100 cm below peat surface with bulk density of 0.1 g cm^{-3}, indicating that soil with fine textured had smaller pores resulting a greater capacity to hold and retain water than coarser soil with larger pores (Nugraha et al., 2016). 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).

2.3.1.2 Temperature

Higher soil temperatures have been reported to enhance soil respiration in tropical peatland (Melling et al., 2005; Ali et al., 2006; Hirano et al., 2009; Ishikura et al., 2017). Both rise of temperature and lower water table at the same time increased soil CO_2 fluxes in peat (Silvola et al., 1996). Soil CO_2 emission from tropical peatland could be lower than from temperate peat (Hadi et al., 2001; Chimner, 2004) which could due to the high content of resistant organic compounds like lignin in tropical peatland (Hadi et al., 2001). In open peat areas, soil temperature positively affected soil CO_2 flux (Schrier-Uijl et al., 2013; Jauhiainen et al., 2014). In other hand, Adachi et al. (2006) reported that in tropic, soil temperature did not correlate with spatial variation in soil respiration rate due to constant soil temperature in tropics. Itoh et al. (2017) showed a weak positive correlation between peat decomposition and soil temperature at site with lacked of canopy. Low temperature sensitivity of soil CO_2 flux was attributable to the small amplitude of soil temperature both on annual and daily bases under the tree canopy (Wakhid et al.,2017). However, Hirano et al. (2014) found that the effect of soil temperature rise on soil CO_2 efflux was small even at an open peatland when GWL was low.

2.3.1.3 Soil pH

Microbial activity is influenced by soil pH. The CO_2 flux tended to be positively correlated with the soil acidity (Murayama and Bakar, 1996). Therefore, management practices such as liming influence soil emissions; additional carbonate can be released as CO_2 (Snyder et al., 2009). CO_2 emissions were observed to be highest at neutral pH-values (Cuhel et al., 2010). Ishikura et al. (2018) showed that CO_2 flux had significant negative relationship with soil pH, suggesting that promotion of organic matter decomposition acidify the soil. In contrast, the neutralization of soil acidity promotes organic matter decomposition in tropical peat soils (Ishikura et al., 2017).

2.3.1.4 Quality of Organic Matter

Production of CO_2 was related to substrate quality, as measured by aromatic/aliphatic and C/N ratios, not substrate quantity (Swails et al., 2017). CO_2 production also declined significantly with increasing C/N ratio and increased with available N, suggesting that N availability was limiting to CO_2 production. Fresh organic matter accumulates at the surface of peat soil. While bigger aggregates contained more fresh organic materials, smaller aggregate contained more broken-down organic matter, making its availability easier to microorganisms. This contention was supported by the lower C/N ratio for aggregate size 0–2mm compared with 2–8mm (Kimura et al., 2012). At sub-surface, high CO_2 emission was found for bigger aggregates, even though its C/N ratio was significantly lower than the smaller aggregate size of 0–2mm. Easily decomposable small organic particles may have disappeared during the formation of the deeper layers, leaving the bigger aggregates more susceptible to decomposition (Kimura et al., 2012). Microaggregates (250 mm diameter) formed by primary particles coupled together by plant and microbial debris and by humic materials or polysaccharide polymers better protect soil organic matter against decomposition than do macroaggregates (4250 mm diameter) (Denef et al., 2001). Soil organic matter with C/N ratios greater than 20 typically requires additional N to support decomposition (Snyder et al., 2009). Surface peat in an open burnt site contained fewer labile compounds (hemicelluloses, extractives, uronic acids, and cellulose) and more recalcitrant acid insoluble lignin than a forest site (Itoh et al., 2017). Threshold water tables for enhanced CO_2 emissions was within the range of -10 to -20 cm below peat surface. Decreases in water table as much as 10 cm still enabled capillary movement of water from lower part to upper part of the microcosms. Once the differences of water depth were 20 cm, for example from 10 cm to -10 cm and from 0 cm to -20 cm, the amount of CO_2 emission increased significantly at all peat humification levels because it further increased the availability of oxygen for peat decomposition by heterotrophic microorganisms while still sufficiently maintaining moisture content. (Lastuti et al., 2016).

2.3.1.5 Nitrogen Fertilization

Studies on the effect of N fertilization on soil CO_2 emission in tropical peatland had been done in sago palm cultivation (Watanabe et al., 2009), 4 year-old oil palm plantation (Sakata et al., 2014), agricultural and degraded land (Jauhiainen et al., 2014) and 7 year-old oil palm plantation (Comeau et al., 2016). Watanabe et al. (2012) and Sakata et al. (2014) did not found significant effect of N fertilization on soil CO_2 emission while Jauhiainen et al. (2014) found an increase in agricultural land but a decrease in degraded land. Comeau et al. (2016) found Rs was 36.9 kg CO_2–C ha^{-1} (7 days)$^{-1}$ greater in the fertilized than in the non-fertilized plots after the first fertilization but after second fertilization, Rs was 72.2 kg CO_2–C ha^{-1} 7 $days^{-1}$ lesser in fertilized than in the non-fertilized plots, indicating that no enhancement was observed after the second fertilization. However, heterotrophic respiration was greater in the fertilized than in the non-fertilized plots after the first and second fertilization but small and transient. If N treatment was not sufficient to bring C/N to the level generally required to meet microbial requirements, microbial respiration in soils likely remained limited by N. A C/N ratio of 24:1 represents the threshold between C limitation and N limitation for microbial growth (Swails et al., 2017). Although high N treatment was sufficient to alleviate N constraints on microbes, but limitation then may have shifted to soil organic matter quality (Swails et al., 2017).

Studies in mineral soils showed that N addition significantly reduced root respiration in larch plantation, Southearn China, but had no significant impacts on heterotrophic respiration, suggesting that the N-induced reduction in soil respiration can mainly be attributed to the decreased root respiration in the study site (Sun et al., 2014). Reduction in soil respiration can mainly be attributed to the decrease in heterotrophic respiration and rhizosphere respiration in N-limited plantation. In severely NN limited soil, N addition did not alleviate carbon limitation for microbes, and thus N addition had no significant impact on microbial activity. Another possible reason for the unchanged heterotrophic respiration could be that soil dissolved inorganic N was not high enough to suppress microbial activity (Sun et al., 2014). In N-limited ecosystems, the heterotrophic respiration mycorrhizal fungal community has been shown to be quite sensitive to N inputs. Under N-limiting conditions, plants invest a substantial fraction of their photosynthates to heterotrophic respiration mycorrhizal to obtain nutrients. When N addition makes the N becomes less limiting, carbon allocation to heterotrophic respiration mycorrhizal symbionts is often reduced due to the decrease in root respiration (Treseder, 2004; Janssens et al., 2010). In semi-arid grassland, low-level N addition increased soil respiration, plant belowground biomass and soil microbial biomass carbon (MBC), while high-level N additions decreased them (Zhu et al., 2016). Together plant belowground biomass and MBC explained 99.4% of variation in mean soil respiration, with plant belowground biomass explaining 63.4% of the variation and soil MBC explaining the remaining 36% (Zhu et al., 2016). Heterotrophic respiration was suppressed by excessive supply of ammonium and nitrate which was more effectively increased by urea (Chen et al., 2018). Tu et al. (2013) reported that N fertilization had no influence on total soil respiration because the higher microbial respiration was offset by the smaller contribution of plant root respiration to total respiration and a lower fine root biomass. In other studies, In larch plantation, N additions significantly decreased Q_{10} of heterotrophic respiration and root respiration in high-N plots by 7% and 13% (Sun et al., 2014). Application of N fertilizer enhanced the Q_{10} value of root respiration, but decreased both of soil respiration and heterotrophic respiration in maize cropland (Chen et al., 2018).

2.4 Production of N_2O in Soil

Production of N_2O in soil is predominantly biological. Nitrous oxide is produced through the processes of nitrification, denitrification, dissimilatory nitrate reduction to ammonium and chemo-denitrification (Hayatsu et al. 2008; Stevens and Laughlin, 1998). It has been well documented that nitrification is the dominant process for the production of N_2O in aerobic soils (Granli and Bøckman, 1994; Inubushi et al. 1996), whereas denitrification is the dominant process under anaerobic conditions (Bollmann and Conrad, 1998; Granli and Bøckman, 1994). As shown in **Figure 2.1**, in soil, NH_3 can be converted into ammonium ion (NH_4^+), which can be oxidized to nitrate ion (NO_3^-), in a three-step process called nitrification. Nitrite (NO_2^-) and NO_3^- ions are generated during nitrification and they may be reduced during the denitrification process, that is the stepwise reduction of NO_3^- to N_2 by four enzymes, generating intermediate products: NO_2^-, NO and N_2O. During the NO_3^- ammonification to NH_4^+, via NO_2^-, it can also occur NO_3^- reduction, thus producing N_2O.

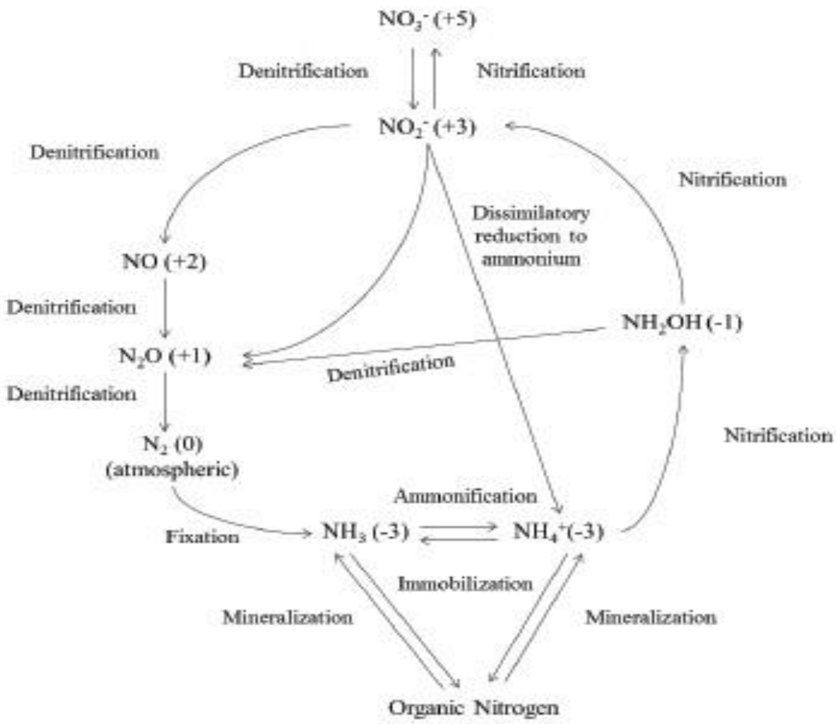

Figure 2.1 Main pathways for N_2O formation in soil (Signor and Cerri, 2014).

2.4.1 Factors Influencing Soil N_2O Emission

2.4.1.1 Soil Moisture and GWL

Similarly to soil respiration, variations in soil water content strongly affect soil emissions of N_2O as it regulates the oxygen availability to soil microbes. Production of N_2O is naturally produced in soil mainly as a by-product of the microbial processes; nitrification and denitrification in aerobic and anaerobic condition, respectively (Lamers et al., 2007). The effect of soil water content on soil N_2O effluxes has been described as a monotonic curve with maximum emissions around field capacity, which is often around 60% of water-filled pore space (WFPS) on which at higher water contents, N_2O is primarily reduced into N_2 (Davidson, 1991). Depending on soil type, N_2O emissions have their optimum in the range of 70–80% water-filled pore space (WFPS) (Davidson et al., 2000). Compaction of the peat before planting, resulting in a reduction in macropore volume and an increase in WFPS, which in turn decreased gas diffusivity in the peat, inhibited the escape of N_2O and enhanced the conversion of N_2O to N_2 (Melling et al., 2007). At WFPS ≥70% in all compaction treatments, high N_2O emissions were a result of denitrification and occurred at a WFPS while N_2 production occurred only at the highest soil moisture level (≥90% WFPS) but it was considerably smaller than the N_2O–N emission (Ruser et al., 2006). Ariffin et al. (2019) found that soil moisture effect was only present after urea addition where it regulated the rate of nitrification. Soil moisture is also controlled by precipitation (Takakai et al., 2006). During wet season, N_2O was produced via denitrification by using NO_3^--N which was accumulated in peat soil by nitrification and mineralization process during dry season, causing N_2O fluxes higher during the rainy season than during the dry season. (Takakai et al., 2006; Hatano et al., 2010).

There is no direct effect of drainage on N_2O emission, however, water table or flooded conditions would enable denitrification of N_2O to proceed further to N_2, resulting in a lower production of N_2O and thus, its potential emission to the atmosphere (Melling et al., 2009). Drainage in peat increases peat mineralization rates and NO_3^- availability, thus the potential for N_2O production would be significantly greater (Hadi et al., 2000; Jauhiainen et al., 2011). Fluctuating water tables promote constantly alternating aeration conditions and thus incomplete denitrification, which is the major N_2O forming process in soil (Lamers *et al*., 2007). Increased frequency of water filtration through the peat and rising water tables after the onset of the wet season improve peat moisture conditions and, with sufficiently oxic conditions in the surface peat, will enhance decomposition of fine root and leaf litter deposited during drier conditions, resulting in the detected surge in N_2O emissions (Jauhiainen et al., 2012). Flooded conditions would enable denitrification to reduce N_2O into N_2 (Inubushi et al., 2003), resulting in lower N_2O emissions. In fertilized systems or systems, drainage increase N_2O emissions. In soils with low pH values, denitrification of N_2O into N_2 at high soil water content may be partially inhibited (Simek and Cooper, 2002).

2.4.1.2 Temperature

Soil temperature is also considered important in regulating the rate of N_2O flux, as the contributions of nitrification and denitrification to N_2O flux may vary with temperature (Koponen et al., 2006; Lai et al., 2019). Lai et al. (2019) reported that nitrification and denitrification peaked at 35–40 °C. However, at temperatures above 40 °C, high soil respiration rates will likely decrease oxygen availability, enhancing the anaerobic microsites, leading to the reduced of N_2O to N_2 production. Increases in peat temperature following drainage, however, particularly in the early stages of plantation establishment (or following replanting) before a closed canopy develops, along with applications of N fertilizers, may counterbalance this effect and maintain high rates of CO_2 emission (Hooijer et al., 2010; Jauhiainen et al., 2011; Murdiyarso et al., 2010). However, low water content in peat can weaken the response of microbial community to temperature (Jaatinen et al 2008; Kwon et al 2013; Davidson and Janssens, 2006). Peat temperature variability is attributed to the high heat capacity and low thermal conductivity of the peat (Soepraptohardjo and Driessen, 1975), which can lead to lasting spatial peat temperature differences if certain shading conditions dominate. Despite to positive relationship, studies found that soil temperature had little influence on observed differences N_2O production (Linn and Doran, 1984) and negative correlation trend in N_2O flux with increasing peat temperatures in fertilized peat, suggesting a 12–36% lower efflux for each 1 °C increase in peat temperature (at 5 cm depth) at the sites (Jauhiainen et al., 2014).

2.4.1.3 Nitrogen Fertilization

Applications of N fertilizer generally serve to increase rates of N_2O emission in peat (Hadi et al., 2000; Takakai et al., 2006). A studies on peat in Palangkaraya, Indonesia showed that a 10 % increase of N fertilizer application potentially increases the N_2O emission by up to 5.6 kg N ha^{-1} yr^{-1}, when fertilizer N increases to 10% of the maximum application of N (163.8 kg N ha^{-1} yr^{-1}) and the N_2O emission factor is 3.6% (Hatano et al., 2016). Ariffin et al. (2019) showed that N addition through urea is the most significant factor inducing mineralization and nitrification in cultivated tropical peat soils. N fertilization at rates up to 160 kg N ha^{-1} in rewetted degraded peat soils does not affect annual N_2O emissions (Morris et al., 2017). Incubation study showed that the addition of ammonium sulphate to tropical peatland suppressed N_2O emissions due to high ammonium content and an anaerobic condition that inhibited nitrification (Hadi et al., 2000). It is likely that the greater part of N_2O fluxes from drained organic soil was derived from N released as a result of peat decomposition, and not from fertilization (Oktarita et al., 2017; Leifeld, 2018). A study on temperate peat showed that N fertilization stimulated N_2O flux only when application rates were very high (480 kg N ha^{-1}) but the N_2O flux hardly increased under 60–120 kg N ha^{-1} application rates even when NO_3^- was high (Augustin et al., 1998). On other hand, Sakata et al. (2014) found that there were no significant effects of the N fertilizer on N_2O emissions in a young oil palm plantation on peat but high N_2O emissions were observed when fertilizer was applied to wet peat soil.

2.5 Annual Cumulative CO_2 and N_2O Emissions from Other Studies

Table 2.1 Annual cumulative CO_2 emissions from other studies on tropical peatland

Author	Location	Land-use	Annual cumulative CO_2 emission (t C ha^{-1} yr^{-1})
Inubushi et al. (2003)	South Kalimantan	Abandoned upland crops field	9.9
		Abandoned paddy fields	15.4
		Secondary forest	12
Melling et al. (2005)	Sarawak	Forest	21.9
		Sago	12
		Oil palm	16.6
Hadi et al., (2005)	Kalimantan	Secondary forest	34.6
		Paddy fields	13.9
		Rice soybean rotation field	20.2
Murdiyarso et al., (2010)	Indonesia	Oil palm	12.7
Husnain et al. (2014)	Sumatra	4-year oil palm	18
		3-year acacia	16.1
		Secondary forest	16.6
		Rubber	14.2
		Bareland	15.3-18.3
Dariah et al., (2014)	Jambi	6-year oil palm	10.4
		15-year oil palm	9.3
Wakhid et al., (2017)	Central Kalimantan	Rubber (Soil respiration)	32.9
Hergoualc'h et al., (2017)	Central Kalimantan	Forest	12.9
		Oil palm 2007	13.8
		Oil palm 2012	11.7
Ishikura et al., (2018)	Sibu, Sarawak	9-year oil palm	
		Close to palm	10.3
		Far from palm	5.9

Table 2.2 Annual cumulative N_2O emissions from other studies on tropical peatland

Author	Location	Land-use	Annual cumulative N_2O emission (kg N ha^{-1} yr^{-1})
Melling et al. (2007)	Sarawak	Forest	0.7
		Sago	3.3
		Oil palm	1.2
Oktarita et al., (2017)	Sumatra	Oil palm	12.8–26.6
Takakai et al., (2006)	Central Kalimantan	Cropland	21-259
		Unfertilized grassland	7.1-23
		Natural forest	0.6-4.4
		Regenerated forest	0.4-4.0
		Burned forest	0.9-1.5
Hadi et al., (2005)	Kalimantan	Secondary forest	13.4
		Paddy field	0.3
		Rice-soybean field	2.0
Jauhiainen et al., (2012)	Central Kalimantan	Drained forest	15.8
		Undrained forest	0.6
		Drained burnt forest	0.7
		Land drained for agriculture	0.2

CHAPTER 3

Materials and Methods

3.1 Field Experiment

3.1.1 Study Site

As described in Chaddy et al. (2019), this study was carried out in an oil palm plantation (*Elaeis guineensis* Jacq.) on tropical peatland in Sibu, Sarawak, Malaysia (2°11’ N, 111°50’ E) (**Figure 3.1**). Sarawak has an average annual air temperature and an annual rainfall of 32.6 °C and 2701 mm, respectively. Generally, the wet season occurs between October and March while the dry season occurs between April and September. The peat in the experimental site is a deep peat of about 9 m depth, classified as *Typic Haplofibrist* based on the USDA soil classification system (Soil Survey Staff, 2014) and Dystric Histosols based on the World Reference Base (WRB) for soil classification systems (2015). The site was cleared and drained in 2007. After the peat surface was flattened with compaction and consolidated using a heavy machine, oil palms were planted in February 2008 at a density of 148 palms ha^{-1} (8.5 m between oil palms in a triangular design). The water table level was initially deeper than −1 m but became shallower and controlled between −50 cm and −70 cm below the soil surface in June 2010 and, therefore, suited for oil palm growth.

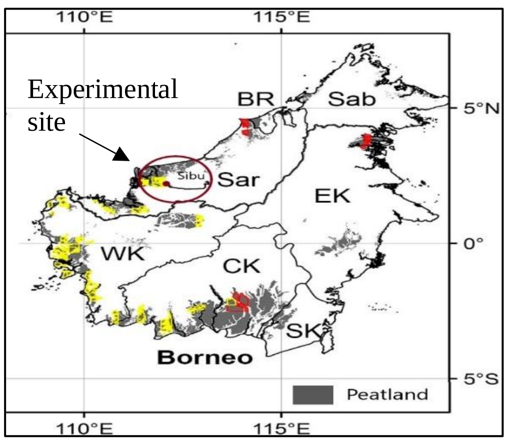

Figure 3.1 Location of experimental site (Source: Miettinen et al., 2016).

3.1.2 Field Experimental Design

The experiment used a randomized complete block design with four different N rates in three blocks (three replications). Each block (1564 m^2) consisted of 36 oil palms of which 16 central palms were selected for the fresh fruit bunch (FFB) collection record while four were selected as the gas sampling points. Each block was separated by 2 to 3 rows of palms or field drains, as shown in **Figure 3.2**. The treatments included the control (T1, without N fertilization), low N (T2, 31.1 kg N ha^{-1}), moderate N (T3, 62.2 kg N ha^{-1}), and high N (T4, 124.3 kg N ha^{-1}). The moderate N rate (T3) in this study was based on the recommended rate by Hasnol et al. (2014). Ammonium sulphate (AS) (21% N) was applied as the N fertilizer four times a year in March, June, September, and November. The rate of N fertilization is shown in **Table 3.1**. Other fertilizers such as rock phosphate (RP), muriate of potash (MOP), copper (Cu), Zinc (Zn), and borate (Bo), were also applied based on the schedule shown in **Table 3.2**. All fertilizers were applied 2 m away from the palm trunk with the width of circumference fertilizer area was approximately 0.15 m. (**Figure 3.2**).

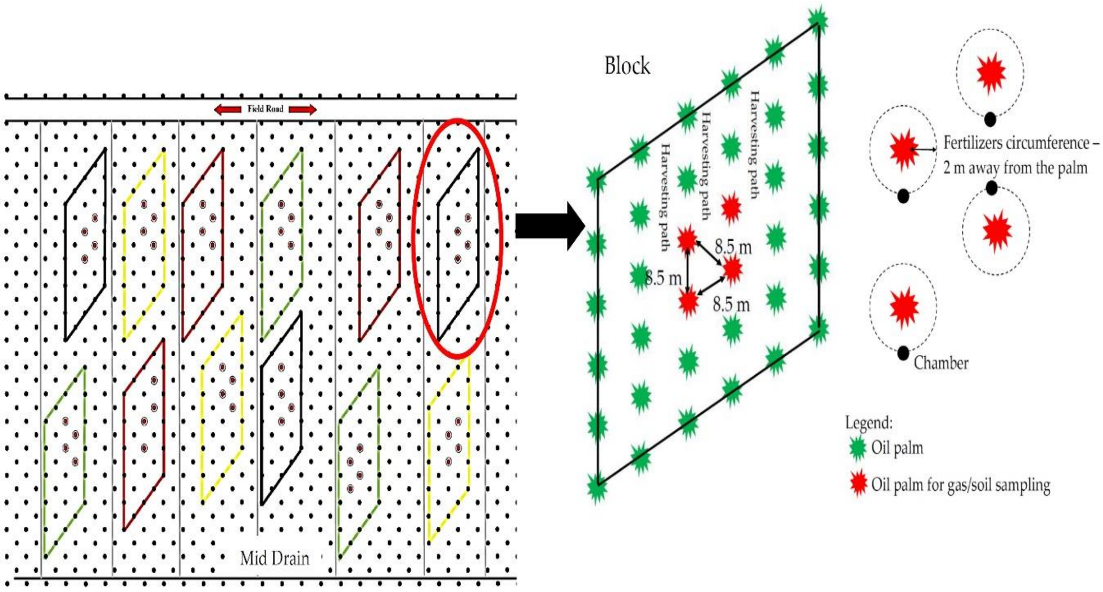

Figure 3.2 A diagram of the experimental design; each color represents different treatments (black—T1, yellow—T2, red—T3, and green—T4) (Chaddy et al., 2019).

Table 3.1 Rate of ammonium sulphate (AS).

Treatment	Month	kg AS palm^{-1}	kg AS palm^{-1} yr^{-1}	kg N ha^{-1} yr^{-1}
T1	March	0	0	0
	June	0		
	September	0		
	November	0		
T2	March	0.25	1	31.1
	June	0.25		
	September	0.25		
	November	0.25		
T3	March	0.5	2	62.2
	June	0.5		
	September	0.5		
	November	0.5		
T4	March	1	4	124.3
	June	1		
	September	1		
	November	1		

Table 3.2 Fertilization schedule from 2010 to 2017 (kg palm^{-1}).

Rate	Feb	Mar			May		June	
	RP	AS	MOP	Cu	Zn	Bo	AS	MOP
T1 (Control)	1.75	0	1	0.1	0.1	0.1	0	1
T2 (Low N)	1.75	0.25	1	0.1	0.1	0.1	0.25	1
T3 (Recommended N)	1.75	0.5	1	0.1	0.1	0.1	0.5	1
T4 (High N)	1.75	1.0	1	0.1	0.1	0.1	1.0	1

Rate	Aug	Sept		Oct			Nov	
	Kieserite	AS	MOP	Cu	Zn	Bo	AS	MOP
T1 (Control)	1.75	0	1.6	0.1	0.1	0.1	0	1.6
T2 (Low N)	1.75	0.25	1.6	0.1	0.1	0.1	0.25	1.6
T3 (Recommended N)	1.75	0.5	1.6	0.1	0.1	0.1	0.5	1.6
T4 (High N)	1.75	1.0	1.6	0.1	0.1	0.1	1.0	1.6

Ammonium sulphate $(NH_4)_2SO_4$ (AS); Rock phosphate $Ca_3(PO_4)_2$ (RP); Muriate of potash (KCl) (MOP); Copper (Cu); Zinc (Zn); Borate (B_2O_3) (Bo). All values are in kilogram (kg).

3.1.3 Gas Flux Measurements

This study was conducted from January 2010 to December 2013, and resumed from January 2016 to December 2017. Gas measurements were done in the first week of every month on a non-rainy day, 1 week after fertilization, using a closed chamber method. The chambers consisted of white-painted stainless-steel rings (25 cm height with a 20 cm diameter) as shown in **Figure 3.3**. Four palms in the middle of each replication plot were selected for the gas sampling. Prior to gas sampling, each chamber for each palm was placed directly into the soil, at a fertilizer spot 2 m away from the selected palm. The soil along the edge of each cylinder was cut with a very sharp knife and the cylinder was pushed into the soil to a depth of 3 cm to prevent leakage of gas from the bottom of the chamber. Height of the chamber was measured at 3 points inside the chamber and left for 30 minutes to achieve stability in the presence of installation disturbance. To attain stability in the presence of installation disturbance, all the chambers were left for 30 minutes upon installation (Norman et al., 1997). Gas emissions in the field were collected between 9 a.m. and 2 p.m. using a gas tight syringe through a three-way valve fitted onto the chamber cover (**Figure 3.3**).

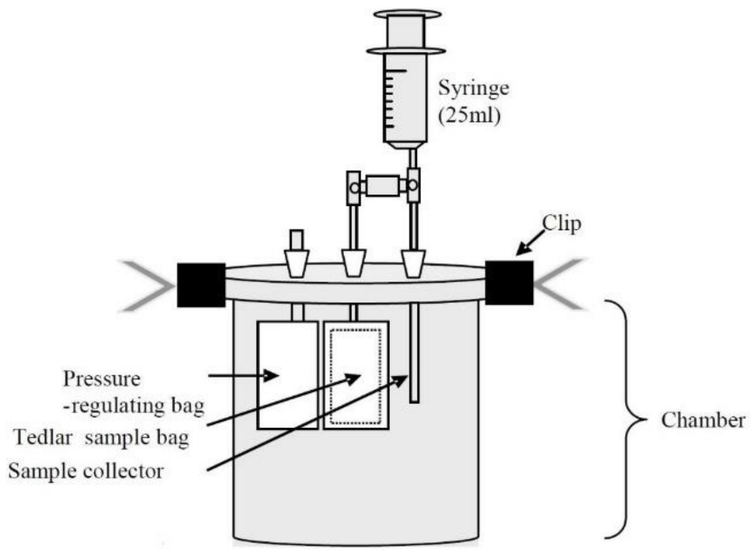

Figure 3.3 Diagram of closed chamber method.

Gas samples in the chamber headspace were taken at 0 and 4 min for CO_2 and 0, 10, 20 and 40 min for N_2O after closing chambers. For CO_2 measurement, upon stability and before closing the chamber, a 500 ml sample of gas from the headspace of each cylinder was extracted into an airtight bag (Tedlar bag) using a gas tight 50 ml polypropylene syringe. This measurement was regarded as time 0 min. The top of each cylinder was then immediately closed with an acrylic cover which had two ports, one for gas sampling and the other for attaching a sampling bag to equilibrate the chamber pressure with the atmospheric pressure. After 4 min under closed-chamber conditions, another 500 ml of headspace gas sample was similarly extracted from each chamber into an airtight bag. Gas for CO_2 determination in the field were collected between 9 a.m. and 11 a.m. As described in Chaddy et al. (2019), a 20 mL gas sample from the headspace of each chamber was extracted using a gas-tight 25 mL syringe and transferred into an evacuated vial for N_2O analysis before closing the chamber. This measurement was regarded as time 0 min. Under closed chamber conditions, another 20 mL gas sample was taken after 10, 20, and 40 min, and then transferred into an evacuated vial. Gas for N_2O determination in the field were collected between 11 a.m. and 2 p.m. Concentration of CO_2 was analyzed within 4 h after sampling using an infrared CO_2 analyzer (ZFP-9, Fuji Electric Systems, Tokyo, Japan). Prior to analysis, infrared CO_2 analyzer was calibrated using a N_2 and 1887 ppm CO_2. In the laboratory, N_2O gas concentrations were determined using an electron capture detector (ECD) gas chromatograph (Agilent Technologies 7890A). Gas emissions were calculated using the following linear regression equation (Jin et al., 2010):

$$F = p \times h \text{ x } (\Delta c/\Delta t) \times (273/(273 + T) \times \alpha$$

where F is the gas flux (mg N m^{-2} hr^{-1} for CO_2 and µg N m^{-2} h^{-1} for N_2O), p is the gas density (CO_2= 1.977 x 10^6 mg m^{-3} for CO_2 and N_2O = 1.978 × 10^9 µg m^{-3}); h is the height of the chamber from the soil surface (m); $\Delta c/\Delta t$ is the change in gas concentration inside the chamber during the sampling period (10^{-3} m^3 m^{-3} h^{-1} for CO_2 and 10^{-6} m^3 m^{-3} h^{-1} for N_2O); T is the average air temperature during the sampling period (0 and 4 min for CO_2 and 0, 10, 20, and 40 min for N_2O) (°C); and α is the conversion factor from CO_2 to C and N_2O to N (i.e., 12/44 for CO_2 and 28/44 for N_2O). A positive flux denotes emission from the soil and a negative flux denotes uptake from the atmosphere. The annual cumulative soil CO_2 and N_2O emissions were calculated from the monthly mean values as follows (Melling et al., 2005; Melling et al., 2007):

$$\text{Annual cumulative gas emission } = \sum_{i=1}^{n-1} Fi \times Di$$

where Fi is the mean gas flux (t ha^{-1} yr^{-1} for CO_2 and kg ha^{-1} day^{-1} for N_2O) between two sampling times (i.e., for time interval i), Di is the number of days in the sampling interval, and n is the frequency of sampling. The emission factor (EF) was calculated using the following formula (Albanito et al., 2017):

$$EF (\%) = (F - C)/N \times 100$$

where F is the annual cumulative N_2O emission emitted from the fertilized treatment (kg N ha^{-1} yr^{-1}), C is the annual cumulative N_2O emissions from the control treatments (kg N_2O-N ha^{-1} yr^{-1}), and N is the annual amount of N application (kg N ha^{-1} yr^{-1}). The EF was calculated when there was a significant difference in N_2O emission between control and fertilized treatments.

3.1.4 Environmental Parameters and Soil Sampling

At the same time that the gas measurement was performed, environmental variables such as air temperature, relative humidity, soil temperature at 5 and 10 cm, groundwater level, and rainfall were also measured. Air temperature and relative humidity were measured using an air temperature and relative humidity meter (TESTO 625, Testo SE & Co. KGaA, Lenzkirch, Germany) while soil temperature was measured using a portable soil temperature meter (Hanna CheckTemp 1, Hanna Instruments Inc, Rhode Island, USA). Groundwater level was measured by installing a PVC perforated pipe into the ground and rainfall was collected and measured using a rain gauge.

Upon completing the gas measurement, soil core samples were collected using a core ring (5 cm diameter, 5.1 cm height) to determine bulk density and the water-filled pore space (WFPS) of the soil inside the chamber. Then, soil at 0–25 cm (higher root density zone) was sampled using a peat auger, after which the chemical characteristics of the soil were further analyzed.

3.1.5 Soil Physico-Chemical Analysis

In the laboratory, undisturbed core samples were then oven dried at 105 °C for 48 h and reweighed to determine their bulk density (Bd) and moisture content. Actual volume (solid and liquid phases) of the soil was measured using three phase meter (DIK-1150; Daiki Rika, Saitama, Japan) for the water-filled pore space (WFPS) and total porosity calculation using following equation:

$$\text{WFPS (\%)} = \frac{\text{A}}{\text{B+A}} \times 100$$

$$\text{Total porosity (\%)} = \frac{\text{C} - \text{D}}{\text{C}} \times 100$$

where A was the weight of water (g); B was the volume of air (g); C was volume of soil (cm^{-3}) in core ring and D was volume of soil particle (cm^{-3}).

Soil samples collected using auger were air-dried and sieved in 2 mm mesh. Soil pH was determined by extracting soil in ultrapure water (1:2.5) and measured using a pH meter (Methrohm 744, Methrohm AG, Herisau, Switzerland). In order to determine nitrate (NO_3^-), sulphate (SO_4^{2-}) and ammonium (NH_4^+), soil was extracted in deionized water and 2 M potassium chloride (KCl), respectively, which then filtered using filter paper. From the water extracts, NO_3^- and SO_4^{2-} concentrations of the soil were analyzed using an ion chromatograph (Methrohm 761 Compact IC, Methrohm AG, Herisau, Switzerland), while from KCl extracts, NH_4^+ was determined using a method proposed by Keeney and Nelson (1982). Loss on ignition (LOI) was determined using a thermogravimetric analyzer (LECO TGA701, LECO Corporation, Michigan, US) while carbon (C) and nitrogen (N) were analyzed using a CN analyzer (LECO TruMac 4060, LECO Corporation, Michigan, US).

3.1.6 Oil Palm Yield Collection

Oil palm yield, parameterized as the fresh fruit bunch (FFB) in each palm of each treatment block, were harvested, weighed, and recorded according to an approximately 7–10-day harvest interval in each month whereas the yearly total was derived using the density of 148 palms ha^{-1}. The number of fruit bunches produced was also recorded. In this study, the production of palm oil started in May 2010; thus the annual oil palm yield was calculated starting from 2011 onwards.

3.2 Incubation Study: Effect of N Fertilization on CO_2 and N_2O Emissions Under Different Level of Soil Moisture

3.2.1 Incubation Set-up

The laboratory incubation study was conducted to examine the effects of N fertilization on CO_2 and N_2O emissions at two different peat moistures for comparison with field study results. Peat soil for incubation study was collected from the depth at 0 to 25 cm in control plot (T1) in field experiment site as shown in **Figure 3.1**. The fresh soil samples were then spread on trays and air dried at room temperature until it reached 40% gravimetric soil moisture content. Live roots and coarse wood were removed which then sieved using 2 mm mesh. Soil was stored at 4 °C prior to incubation. Soil was incubated with four fertilization treatments at two different soil moisture were arranged by a randomized complete design as shown in **Table 3.3**. Ammonium sulphate was used as N fertilizer in this study. Prior to incubation, 200g of dry peat soil for each treatment was prepared in a plastic bag. For fertilized treatment (T2, T3 and T4), AS and deionised water as in **Table 3.3** was mixed until AS completely dissolved in deionised water. Afterwards, the AS solution was mixed with 200g dry peat soil homogeneously. Then, about 20g soil was taken from the fertilized 200g soil and put into plastic container. The plastic container contained soil was placed into 1.5 L Mason jars and sealed air tightly (**Figure 3.4**). Five replications for each treatment for gas sampling were prepared which was in total 40 jars while one replication for each treatment was prepared for soil chemical analysis. Ambient wet compressed air was passed through a vinyl tube connected to the jar at a rate of 2.0 L min^{-1} for 5 min to replace the gas in the jar completely. Incubation was conducted by placing all the jars in an incubator at 28 ℃ for 12 weeks. After each gas and soil sampling, the same compressed ambient air was flushing through each jar by the same way initially which was done weekly.

Table 3.3 Incubation treatments

ID	N rates (mg kg^{-1} dry soil)	% WFPS
T1	0	
T2	780	50
T3	1,550	
T4	3,110	
T1	0	
T2	780	80
T3	1,550	
T4	3,110	

Figure 3.4 Incubated soils in 1.5 L Mason jar

3.2.2 Gas Sampling and Analysis

Gas sampling was carried out 12 times in weekly basis, at 1,2,3,4,5,6,7,8,9,10,11 and 12 weeks. A 20 mL gas sample from the headspace of each jar was extracted using a gas-tight 25 mL syringe and transferred into an evacuated vial for CO_2 and N_2O analysis. N_2O concentration of gas samples was determined by a gas chromatography with electron capture detector (ECD) (model GC-2014, Shimadzu, Kyoto, Japan) while CO_2 concentration was determined using infrared CO_2 analyzer (ZFP9GC11, Fuji Electric, Tokyo, Japan). Gas flux was estimated using the following equation:

$$F = p \times \frac{V}{W} \times \frac{c}{t} \times \alpha$$

where F is the gas flux (CO_2=mg C kg^{-1} d^{-1}, N_2O= mg N kg^{-1} d^{-1}); ρ is the density of each GHG at the standard conditions (CO_2 = 1.977 kg m^{-3}, N_2O = 1.978 kg m^{-3}); V (m^3) is the volume of the incubation jar; W (kg) is the oven soil weight; c (mg kg^{-1}) is the gas concentration in the jar; t is the incubation period (d) and α is the conversion factor from CO_2 to C and N_2O to N (i.e., 12/44 for CO_2 and 28/44 for N_2O). The cumulative gas flux during incubation (mg kg^{-1} 12 w^{-1}) was calculated as follows:

$$\text{Cumulative gas emission} = \sum_{i=1}^{n} Fi \times Di$$

where Fi is the mean gas flux (CO_2=mg C kg^{-1} d^{-1}, N_2O=mg N kg^{-1} d^{-1}) between two sampling times, Di is the number of days in the sampling interval, and n is the frequency of sampling.

3.2.3 Soil Chemical Analysis

Before incubation, initial chemical analysis for each treatment was done to determine water extractable organic carbon (WEOC), nitrite (NO_2^-), NO_3^- and SO_4^{2-}, soil pH, soil electric conductivity (EC), NH_4^+, total C, total N, and microbial biomass carbon (MBC). Similar to gas sampling, soil was also collected every week for aforementioned analysis. Soil was extracted with deionized water (1:25) for WEOC, NO_2^-, NO_3^- and SO_4^{2-}, soil pH and electric conductivity (EC) determination, and extracted with 2 M KCl (1:25) for NH_{4+} determination. All the extracts were shake for 1 hr, filtered through 0.2-um membrane filters and stored at 4 °C until analysis. Water extractable organic carbon (WEOC) was determine using Tyurin's method (Orlov, 1985) while nitrite (NO_2^-), NO_3^- and SO_4^{2-} concentrations were determined using ion chromatograph (ICS-1100; Thermo Fisher Scientific, Waltham, MA, USA). Soil pH and EC was determined using a combined electrode pH meter (F-8 pH meter; Horiba, Kyoto, Japan) and conductivity meter (CM-30V; TOA electrochemical measuring instruments, Tokyo, Japan), respectively. Total C and N were analyzed using a CN analyzer (LECO TruMac 4060, LECO Corporation, Michigan, US). Concentration of NH_4^+ content was determined by indophenol-blue method using UV-vis spectrophotometer (UV-1240; Shimadzu, Japan). Soil MBC was measured every week by chloroform-fumigation method and analyzed using a total organic C (TOC) analyzer (TOC-V CPH, Shimadzu, Japan). MBC was calculated by the following formula:

$$\mathrm{MBC} = \frac{\Delta \mathrm{C}}{\mathrm{k}}$$

where ΔC is the difference in concentration of organic C extracted by 0.5 M K_2SO_4 between fumigated and non-fumigated soil samples (mg kg^{-1}), and k=0.43 is a factor (Martens, 1995).

3.2.4 Gross N Mineralization, Net N Mineralization and Nitrification

Gross mineralization (GM) was estimated by dividing heterotrophic respiration which (refers to CO_2 flux in this incubation study) (Rh) by C/N ratio (Luxhoi et al. 2006):

$$\mathrm{GM} = \frac{\mathrm{Rh}}{\mathrm{C/N\ ratio}}$$

Net mineralization and nitrification were calculated by following equation (Cardoso et al., 2011):

$$\text{Net mineralization} = \frac{(\mathrm{NH_{4^+}} - \mathrm{N} + \mathrm{NO_3^-} - \mathrm{N})\ \text{final} - (\mathrm{NH_{4^+}} - \mathrm{N} + \mathrm{NO_3^-} - \mathrm{N})\text{initial}}{\text{Incubation time (day)}}$$

$$\text{Net nitrification} = \frac{(\mathrm{NO_3^-} - \mathrm{N})\text{final} - (\mathrm{NO_3^-} - \mathrm{N})\text{initial}}{\text{Incubation time (day)}}$$

3.3 Statistical Analysis

One-way analysis of variance (ANOVA), two-way ANOVA and Tukey's HSD were performed to test the significance of variable across the treatments (Chapter 4 to 6). A stepwise multiple regression analysis and Pearson's Correlation were conducted to identify the main factors influencing CO_2 and N_2O emissions as well as the environmental parameters and soil properties. For incubation study, two-way ANOVA was used to evaluate the effect of different N treatments and soil moisture on CO_2, N_2O and soil properties. Pearson's correlation test was conducted to identify the main factors influencing CO_2 and N_2O. All statistical considerations were based on $p < 0.05$ significant level. All statistical analyses were conducted using SPSS Statistics Software version 21 (IBM, New York, USA).

CHAPTER 4

Soil N_2O Emissions under Different N Rates in an Oil Palm Plantation on Tropical Peatland

4.1 Introduction

Nitrous oxide (N_2O) is one of the most potent greenhouse gases, with 298 times the global warming potential (GWP) of CO_2 over a 100-year timescale (Forster et al., 2007). Agricultural soils are responsible for 60%–80% of anthropogenic N_2O sources; mainly derived from synthetic fertilizers, manure applications, and crop residues left on farms (Davidson, 2009; Maraseni and Qu, 2016). The drive to fulfill the global demand for food supply and the scarcity of other suitable lands for agriculture has pushed the expansion of oil palm plantations into lowland tropical peatland. Drainage in tropical peatland is strengthened to create oxic conditions for palm growth, with an optimum water table depth of 50–75 cm (Comte et al., 2012). Furthermore, nitrogen (N) fertilization is added to promote palm productivity. In Malaysia, the recommended annual N fertilizer for immature and mature oil palms established on tropical peat soil is 50–100 kg N ha^{-1} yr^{-1} and 120–160 kg N ha^{-1} yr^{-1}, respectively (Mutert et al., 1999). However, both will likely stimulate peat decomposition and mineralization, enhancing N_2O emission from the soil (Jauhiainen et al., 2012; Couwenberg et al., 2010; Murdiyarso et al., 2010).

The N_2O emissions from soils are produced by the microbial processes of nitrification (conversion of NH_4^+ to NO_3^-) in aerobic condition and denitrification (NO_3^- to N_2O or N_2) in anaerobic condition (Jauhiainen et al., 2012; Butterbach-Bahl et al., 2013). Takakai et al. (2006) found that N_2O emission from vegetable fields on tropical peatland significantly increased in the wet season and, although NO_3-N still accumulated in the soil in the dry season, N_2O emission was low. Therefore, denitrification is believed to be a significant emitter of N_2O and that soil moisture is a major environmental factor controlling the N_2O emissions, as it regulates the oxygen availability to soil microbes, affecting the process of denitrification and nitrification (Butterbach-Bahl et al., 2013). One study observed nitrification as the dominant N_2O-producing process in all soils with 60% water-filled pore space (WFPS) while 70% WFPS peat soil was dominated by denitrification (Pihlatie et al., 2004). Groundwater level (GWL) governs the anaerobicity and mineralization rate of soil (Van Beek et al., 2011). Dobbie and Smith (2006) found that rises in GWL were associated with increases in the WFPS of topsoil. The lowering of GWL was mainly reported to increase N_2O emissions by introducing an oxic layer, enhancing peat decomposition and thus nitrogen mineralization (Jauhiainen et al., 2012; Regina et al., 1999). However, another study reported that the presence of groundwater enhanced N_2O production through denitrification (Dobbie and Smith, 2006; Minakawa et al., 2013). Factors such as soil pH, precipitation (Sakata et al., 2014), and NH_4^+ and NO_3^- concentration (Melling et al., 2007; Oktarita et al., 2017) have also been identified to affect soil N_2O emissions.

Only a few studies on soil N_2O emissions from oil palm plantation on tropical peatland (Sakata et al., 2014; Melling et al., 2007; Oktarita et al., 2017) have been carried out. Of these studies, Oktarita et al. (2017) conducted the only long-term study. Sakata et al. (2014) found that there were no significant effects of the N fertilizer on N_2O emissions in a young oil palm plantation on peat but high N_2O emissions were observed when fertilizer was applied to wet peat soil. They concluded that N fertilizer had insignificant effects on annual N_2O emissions because of the predominantly high emissions resulting from peat decomposition (Takakai et al., 2006; Oktarita et al., 2017). Meanwhile, Hadi et al. (2000) reported that the addition of ammonium sulphate to soil significantly reduced the emission of N_2O compared to the control treatments because of the high ammonium content that inhibited nitrification.

Emissions of N_2O are typically erratic, often occurring as pulse events. They are also spatially variable and hard to predict, as they are generally not well correlated with any single environmental factor (Page et al., 2011). Thus, more information and understanding of the key factors influencing the response of soil N_2O emissions due to N fertilization, besides urea, is necessary to develop approaches to mitigate N_2O emissions from cultivated tropical peatland. Finding a suitable nitrogen rate for optimum oil palm growth and yield whilst maintaining low environmental impact is also crucial for the economic growth of the oil palm sector in Malaysia.

In this study, long-term monitoring was conducted to quantify soil N_2O emissions by varying the rates of N fertilizers and the key factors influencing the response of soil N_2O emissions under N fertilization were identified as per Chaddy et al. (2019).

4.2 Materials and Methods

As described in Chapter 3, long-term measurement of N_2O fluxes were done using closed chamber method in an oil palm plantation (*Elaeis guineensis* Jacq.) located in a tropical peatland in Sarawak, Malaysia from January 2010 to December 2013 and resumed from January 2016 to December 2017. The experiment used a randomized complete block design with four different N rates; control (T1, without N fertilization), low N (T2, 31.1 kg N ha^{-1}), moderate N (T3, 62.2 kg N ha^{-1}), and high N (T4, 124.3 kg N ha^{-1}) in three blocks (three replications). Environmental variables such as air temperature, relative humidity, soil temperature at 5 cm and 10 cm, groundwater level, and rainfall were also measured. Soil properties such as bulk density, water-filled pore space (WFPS), soil nitrate (NO_3^-), ammonium (NH_4^+), loss on ignition (LOI), carbon (C), nitrogen (N) were also measured. Oil palm yield, parameterized as the fresh fruit bunch (FFB) in each palm of each treatment block, were harvested, weighed, and recorded. The emission factor (EF) was calculated as shown in Chapter 3

(Section 3.1.3). One-way ANOVA and Tukey's test was used to compare the mean difference ($p < 0.05$) of the given variable across the treatments. A stepwise multiple regression analysis and Pearson's correlation were conducted to identify the main factors influencing N_2O emissions as well as the environmental parameters and soil properties.

4.3 Results

4.3.1 General Soil Properties

The physicochemical properties of soil in the control plot are shown in **Table 4.1**. The groundwater level (GWL) recorded an average of −53.0 ± 20.4 cm below the peat surface and the water-filled pore space (WFPS) was 70.4 ± 10.4%. The bulk density in the study site was 0.24 ± 0.01 g cm^{-3}-a result of compaction and consolidation upon drainage. The soil pH was 3.4 ± 0.1 and the loss on ignition (LOI) was 96.7 ± 1.0%. A high soil C/N ratio (30.3 ± 2.4) was recorded due to the higher C content (55.8 ± 2.4%) of the soil. Since the peat was ombrogenic, it had high acidity and high C content.

Table 4.1 Descriptions and physicochemical properties of soil at the study site (mean ± STD). WFPS: water-filled pore space; GWL: groundwater level; LOI: loss on ignition.

Properties	**Value ± SD**
Average annual rainfall (mm)	2697 ± 596.7
WFPS (%)	70.4 ± 10.4
GWL (cm)	−53.0 ± 20.4
Bulk density (g cm^{-3})	0.24 ± 0.01
Soil pH	3.4 ± 0.1
LOI (%)	96.7 ± 1.0
C (%)	55.8 ± 2.4
N (%)	1.9 ± 0.2
C/N ratio	30.3 ± 2.4

4.3.2 Ground Water Level, WFPS, and Soil Temperatures

The monthly rainfall, WFPS, GWL, and soil temperatures are shown in **Figure 4.1**. There is a clear seasonal pattern in the rainfall (**Figure 4.1 (a)**). The GWL pattern generally follows the rainfall pattern (**Figure 4.1 (b)**). The short-term low GWL for all treatments was observed between January 2010 and June 2010, ranging from −76 cm to −109 cm below the peat surface. The GWL increased beginning from July 2010 onwards, ranging from −23 cm to −101.5 cm below the peat surface. A lower GWL was also clearly observed from June 2011–December 2011, June 2016–December 2015, and June 2017–September 2017 (**Figure 4.1 (b)**). A lower WFPS was observed from January to June 2010 ranging between 51% and 70%, coinciding with the lower GWL in the same period. The WFPS in all treatments eventually increased with time, ranging from 59% to 95.9% (**Figure 4.1 (c)**). The significant differences ($p < 0.05$) of WFPS between continuous low GWL (−76 cm to −109 cm) and high GWL (−24 cm to −58.3 cm) in 2010 are shown in Table 4. However, from 2010 to 2012, the pattern of WFPS (ranging from 51% to 82.1%) was mainly influenced by the pattern of GWL. After 2012, the pattern of WFPS increased with an increase in the age of the palm, to range from 71% to 95.9% (**Figure 4.1 (c)**).

Soil temperature at 5 cm and 10 cm depth did not show a clear seasonal or annual trend and remained in the range of 26.6 °C to 30.0 °C (**Figure 4.1 (d)**).

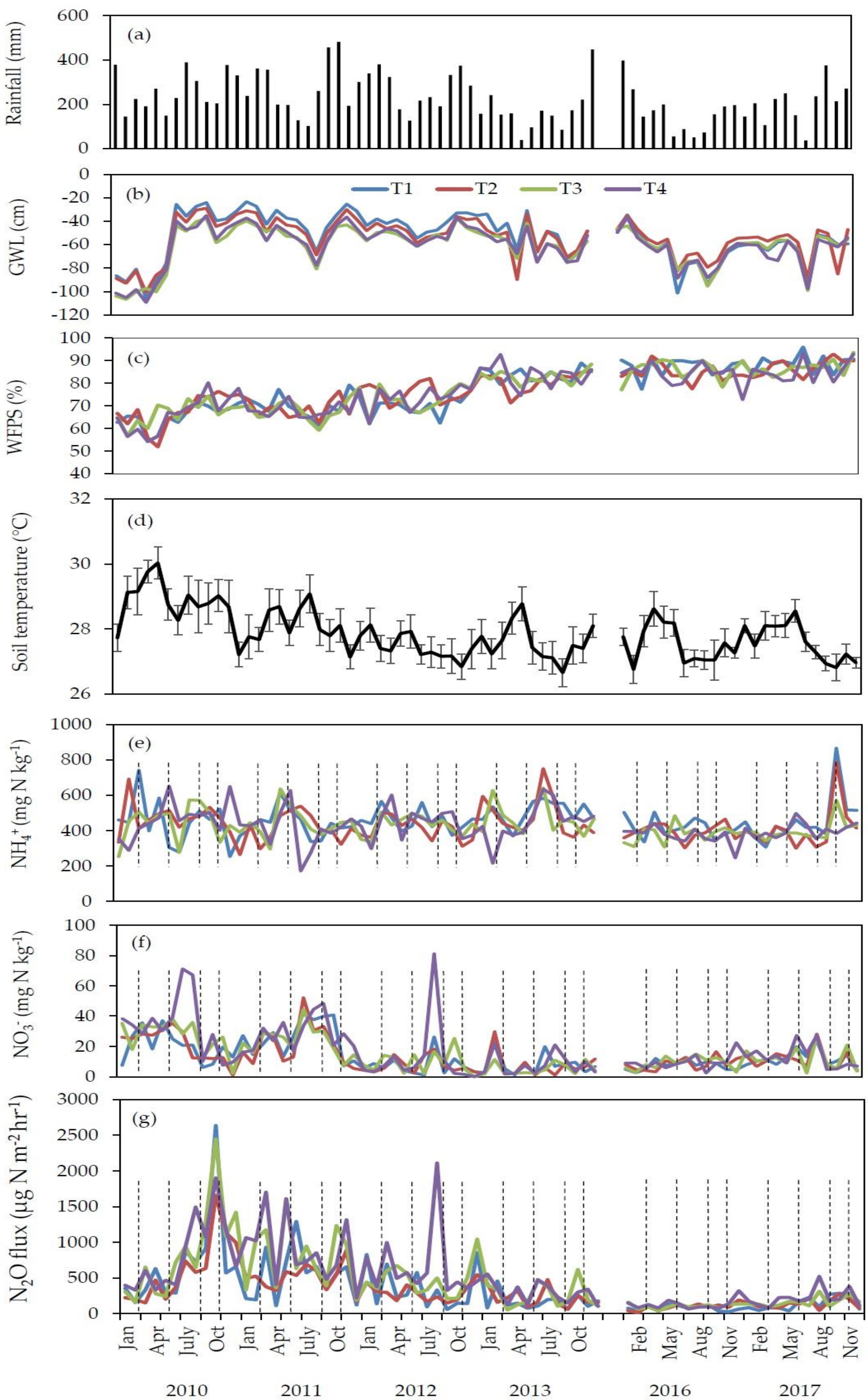

Figure 4.1 Monthly (a) rainfall, (b) GWL, (c) WFPS, (d) soil temperature, (e) NH_4^+-N, (f) NO_3^--N concentrations and (g) N_2O fluxes for each treatment. The dashed line indicates N fertilization (applied every March, June, September, and November of each year).

4.3.3 Soil NH_4^+ and NO_3^- Concentrations

As shown in **Figure 4.1**, the soil NH_4^+ for all treatments were higher than the soil NO_3^- throughout this study, indicating that inorganic-N was dominated by NH_4^+ at the study site. The variations in NH_4^+ among the treatments were small, ranging from 253–865.2 mg N kg^{-1}, 263–785.7 mg N kg^{-1}, 253–641.5 mg N kg^{-1}, and 171–651.6 mg N kg^{-1} for T1, T2, T3, and T4, respectively. Following N fertilization, small peaks of NH_4^+ could sometimes be observed (**Figure 4.1 (e)**). Short-term GWL changed in 2010 but did not significantly affect NH_4^+ either between treatments or between both low and high GWL conditions for each treatment ($p > 0.05$) (**Table 4.2**). The N fertilization had no effect on NH_4^+ in each year ($p > 0.05$).

The soil NO_3^- varied from 1.1–41.9 mg N kg^{-1}, 1.0–52.0 mg N kg^{-1}, 1.8–44.5 mg N kg^{-1}, and 1.5–81.1 mg N kg^{-1} for T1, T2, T3, and T4, respectively (**Figure 4.1 (f)**). Generally, small peaks denoting NO_3^- concentration were observed upon N fertilization. Variation in NO_3^- was generally driven by the GWL pattern, especially from 2010 to 2012. A significant negative correlation was consistently found between GWL and NO_3^- from 2010 to 2012 ($p < 0.05$) (**Table 4.3**). High soil NO_3^- concentrations were recorded from January 2010 to June 2010 and then decreased mainly from June 2010 to June 2011 for all treatments except for T4 where higher concentrations were observed in July 2010 and August 2010 upon N fertilization. A wider peak of NO_3^- for all treatments appeared in July 2011 to September 2011 following N application, also coinciding with a drop in GWL (**Figure 4.1 (b)**). Soil NO_3^- concentrations for all treatments became constantly low afterwards except for T4 in August 2012 where the highest peak of NO_3^- concentration (81.1 mg N kg^{-1}) of T4 appeared two months after N application (**Figure 4.1 (f)**). Significant effects of N application on soil NO_3^- were only observed in 2010 with only T4 being significantly higher than the control ($p < 0.05$). The changes in GWL in 2010 had a significant effect on NO_3^- for T1 and T2, as the high GWL significantly decreased NO_3^- concentration. The N rates only had an effect at high GWL with only T4 denoting significantly increased NO_3^- at high GWL (**Table 4.2**).

4.3.4 Soil N_2O Emissions

The highest N_2O fluxes were generally recorded for T4. The N_2O fluxes varied from 28.43–2635 µg N m^{-2} hr^{-1}, 17.19–1658.41 µg N m^{-2} hr^{-1}, 38.07–2447.36 µg N m^{-2} hr^{-1}, and 45.63–2110.94 µg N m^{-2} hr^{-1} for T1, T2, T3, and T4, respectively (**Figure 4.1 (g)**). Higher soil N_2O emissions for all treatments were observed mainly in 2010, 2011, and 2012 compared to 2013, 2016, and 2017. In 2010, peaks of N_2O fluxes appeared following N fertilization in most of the N fertilized treatments. Emissions of N_2O still increased 2 to 3 months upon N application, particularly for T4. The N_2O flux for T4 was significantly higher (1493.84 µg N m^{-2} hr^{-1}) than other treatments (where T1, T2, and T3 were 728.04 µg N m^{-2} hr^{-1}, 581.55 µg N m^{-2} hr^{-1}, and 649.67 µg N m^{-2} hr^{-1}, respectively) in August 2010 ($p < 0.05$). The peak N_2O flux occurred in October 2010 for all treatments following N application, with the control recording the highest flux. The peak of N_2O flux for T4 was significantly higher than other treatments upon N application in August 2012 ($p < 0.05$), coinciding with a higher peak concentration of NO_3^- for T4 in the same month. In 2013, the pattern of N_2O emissions started to decrease with a decrease in NO_3^- (**Figure 4.1 (f)** and **(g)**).

Besides N fertilization, the patterns of N_2O fluxes were also driven by the pattern of GWL and WFPS, particularly in 2010, where continuously lower GWL occurred between January to June 2010 before it started to increase in July 2010 (**Figure 4.1 (b)** and **(c)**). A comparison of N_2O emissions from all treatments between the low GWL and high GWL periods in 2010 is shown in **Table 4.2**. At a lower GWL (−76 cm to −109 cm), N_2O emissions ranged from 155–630.22 µg N m^{-2} hr^{-1} for T1, 152–474.5 µg N m^{-2} hr^{-1} for T2, 159–721.89 µg N m^{-2} hr^{-1} for T3, and 330–607.64 µg N m^{-2} hr^{-1} for T4. Meanwhile, at a higher GWL

(−24 cm to −58 cm), N_2O fluxes for T1, T2, T3, and T4 ranged from 661–2635 μg N m^{-2} hr^{-1}, 581–1658 μg N m^{-2} hr^{-1}, 649–2447 μg N m^{-2} hr^{-1}, and 664–1902 μg N m^{-2} hr^{-1}, respectively. There were no significant effects of N fertilizers on N_2O fluxes in both GWL conditions (low GWL $p = 0.24$; high GWL $p = 0.48$) for all treatments but a rise in GWL significantly increased N_2O emissions by 185% to 253% at low GWL ($p < 0.05$). A pattern of higher soil N_2O emissions were continuously observed up until 2012.

The annual cumulative N_2O emissions for each year for all treatments are shown in **Table 4.4**. The annual cumulative N_2O emissions for T1, T2, T3, and T4 ranged from 6.5–47.4 kg N ha^{-1} yr^{-1}, 7.6–43.5 kg N ha^{-1} yr^{-1}, 8.2–70.7 kg N ha^{-1} yr^{-1}, and 9.8–79.7 kg N ha^{-1} yr^{-1}, respectively. The application of N fertilizer significantly increased the annual cumulative N_2O emissions only for T4 in 2010 ($p = 0.017$), 2011 ($p = 0.012$), 2012 ($p = 0.007$), and 2016 ($p = 0.048$), which were significantly higher than the control by 48%, 68%, 96%, and 52% in 2010, 2011, 2012 and 2016, respectively. This was also reflected in the N_2O EF whereby T4 induced an EF ranging between 2.7% and 25.9% with the highest N_2O EF recorded in 2011 (**Table 4.5**). Only T4 was calculated for EF because only T4 was found to have significant effects on annual cumulative N_2O emissions (**Table 4.4**). The annual cumulative N_2O emissions for all treatments started to significantly decrease in 2012, coinciding with increased WFPS and decreased NO_3^- (**Figure 4.1 (c)** and **(f)**). The highest average annual cumulative N_2O emissions were recorded for T4 (41.5 ± 28.7 kg N ha^{-1} yr^{-1}), followed by T3 (35.1 ± 25.7 kg N ha^{-1} yr^{-1}), T1 (25.2 ± 17.8 kg N ha^{-1} yr^{-1}), and T2 (25.1 ± 15.4 kg N ha^{-1} yr^{-1}), indicating that the N rates of 62.2 kg N ha^{-1} yr^{-1} and 127.7 kg N ha^{-1} yr^{-1} increased the average annual cumulative N_2O emissions by 39% and 65%, respectively, compared to the control.

Table 4.2 Mean WFPS, NO_3^- concentrations, NH_4^+ concentrations, and N_2O emissions for each treatment at low GWL (−76 cm to −109 cm) (January–June) and at high GWL (−24 cm to 58.3 cm) (July–December) in 2010.

Properties	**GWL**	**T1**	**T2**	**T3**	**T4**
WFPS (%)	Low	61.5 (7.0)^{a}	61.4 (7.4)^{a}	64.0 (6.4)^{a}	59.7 (7.1)^{a}
	High	68.0 (7.0)^{a*}	72.2 (6.6)^{a*}	69.3 (7.8)^{a*}	71.3 (6.3)^{a*}
NO_3^- (0–25 cm)	Low	25.0 (14.7)^{a}	28.9 (11.2)^{a}	31.9 (18.1)^{a}	34.8 (10.6)^{a}
(mg N kg^{-1})	High	14.7 (8.6)^{b*}	14.1 (14.0)^{b*}	20.8 (14.8)^{ab}	33.7 (33.9)^{a}
NH_4^+ (0–25 cm)	Low	489.1 (182.7)^{a}	484.6 (144.4)^{a}	440.0 (188.7)^{a}	436.7 (143.8)^{a}
(mg N kg^{-1})	High	411.5 (144.6)^{a}	460.8 (481.7)^{a}	447.4 (134.6)^{a}	497.2 (192.3)^{a}
N_2O	Low	343.7 (240.4)^{a}	270.9 (144.9)^{a}	394.4 (340.0)^{a}	424.1 (200.9)^{a}
(μg N m^{-2} hr^{-1})	High	1063.9 (920.7)^{a*}	957.0 (621.3)^{a*}	1304.8 (729.5)^{a*}	1209.9 (564.3)^{a*}

The data represents the mean (standard deviation) (n = 18). The different letters show the significant differences among the treatments ($p < 0.05$). The asterisk (*) indicates significant differences between low and high GWL ($p < 0.05$).

Table 4.3 Pearson's correlation coefficient denoting the effect of GWL on NO_3^- concentrations for each year (n = 48).

	2010	**2011**	**2012**	**2013**	**2016**	**2017**
GWL	−0.348*	−0.527**	−0.297*	−0.054	−0.418**	0.003
	0.015	0.000	0.043	0.714	0.003	0.981

**Correlation is significant at the 0.01 level (2-tailed). *Correlation is significant at the 0.05 level (2-tailed).

Table 4.4 Annual cumulative N_2O emissions for each treatment.

Year	Annual cumulative N_2O emissions (kg N ha^{-1} yr^{-1})			
	T1	T2	T3	T4
2010	45.9 (11.5)$^{b\ AB}$	43.5 (5.3)$^{b\ A}$	60.4 (11.7)$^{ab\ A}$	67.8 (9.7)$^{a\ A}$
2011	47.5 (4.2)$^{b\ A}$	43.3 (2.5)$^{b\ A}$	70.7 (22.2)$^{ab\ A}$	79.7 (3.3)$^{a\ A}$
2012	25.9 (11.3)$^{b\ BC}$	24.9 (6.2)$^{b\ B}$	36.8 (5.4)$^{ab\ BC}$	50.7 (2.8)$^{a\ B}$
2013	13.59 (4.6)$^{a\ C}$	19.4 (3.2)$^{a\ BC}$	20.9 (7.0)$^{a\ CD}$	22.9 (3.8)$^{a\ C}$
2016	6.5 (0.3)$^{b\ C}$	7.6 (1.6)$^{ab\ D}$	8.2 (0.6)$^{ab\ D}$	9.8 (1.6)$^{a\ C}$
2017	12.2 (5.1)$^{a\ C}$	11.8 (1.0)$^{a\ D}$	13.4 (0.1)$^{a\ CD}$	18.2 (3.3)$^{a\ C}$
Mean	25.2 (17.8)^{a}	25.1(15.4)^{a}	35.1 (25.7)^{a}	41.5(28.7)^{a}

The data presents the mean (standard deviation) (n = 3–12). The letters (a, b, c) in the row indicate a significant difference between treatments while the letters (A, B, C) in the column indicate a significant difference between years using Tukey's Test at $p < 0.05$.

Table 4.5 N_2O emission factor (EF) (%) for T4 (kg N_2O-N [kg N input]$^{-1}$)

	N_2O EF (%)			
	2010	2011	2012	2016
T4	17.14	25.28	19.45	2.63

Data represent mean (standard deviation) (n=3).

4.3.5 Oil Palm Yield

The oil palm in this study started to produce yield in May 2010 for all treatments (**Figure 4.2**). An increasing trend could be observed from May 2010 until December 2013. The yield productions of all treatments were increased in October 2011 to November 2011. A trend of higher oil palm yield from all treatments was observed in December 2012 and remained high up until December 2013. A higher annual oil palm yield for all treatments was recorded in 2013 and followed by 2017 i.e., more than 30 t ha^{-1} yr^{-1}. The oil palm yields decreased in 2016 and started to increase again in 2017. However, N fertilization had no significant effect on annual oil palm production in each year (p = 0.994). Negative relationship was found between annual oil palm yield and annual N_2O fluxes and NO_3^- for overall treatment (**Figure 4.3**) while positive relationship was found between WFPS and oil palm yield (p<0.001) (**Figure 4.4).**

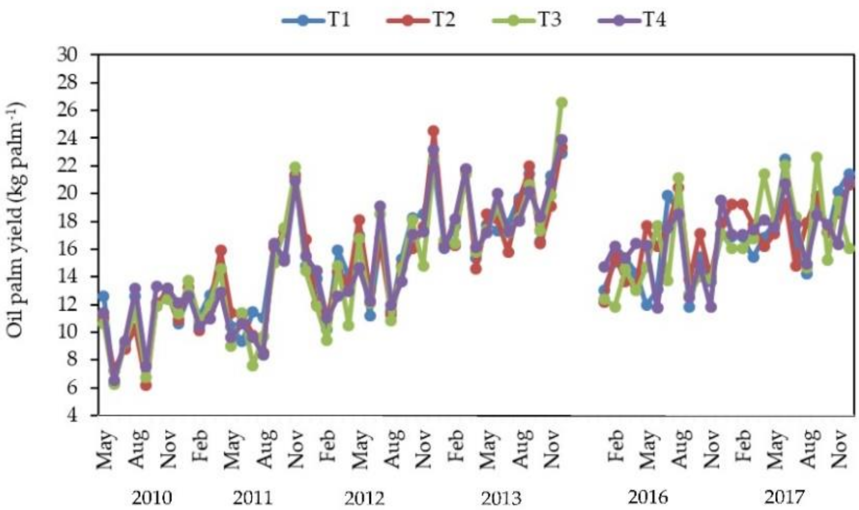

Figure 4.2 Oil palm yield for each treatment (2010–2017).

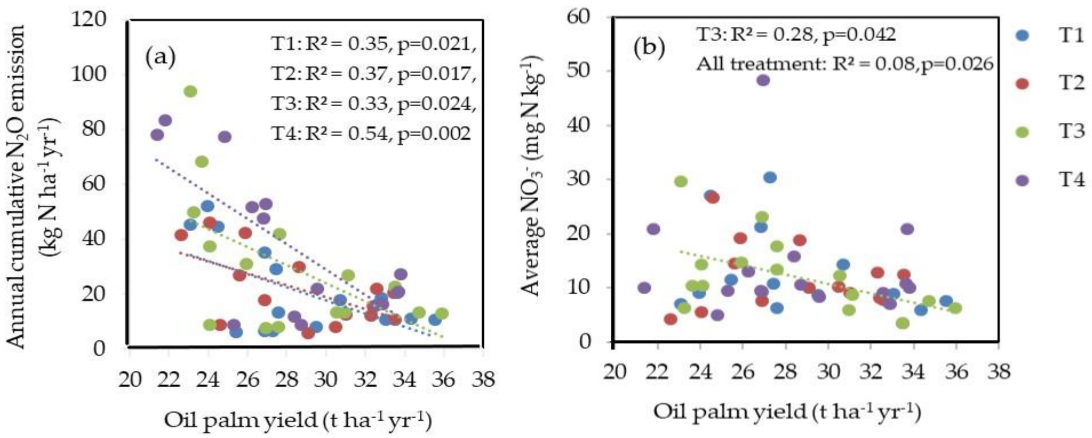

Figure 4.3 Relationships between oil palm yields and annual cumulative N_2O emissions (**a**); and between oil palm yields and NO_3^- (**b**) for each treatment.

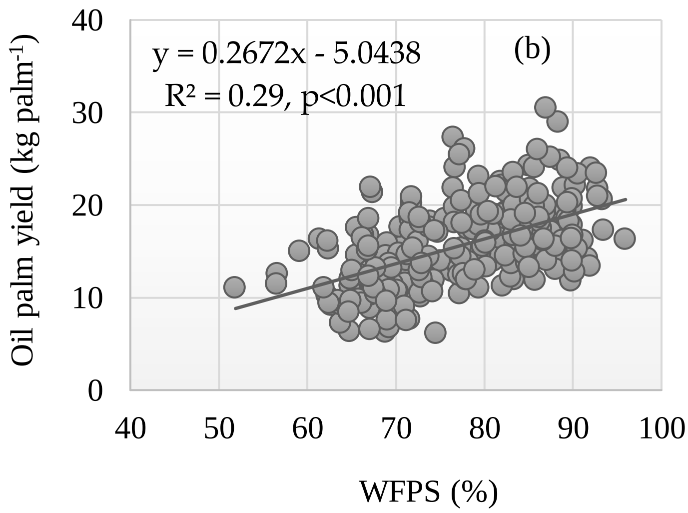

Figure 4.4 Relationship between WFPS and oil palm yield.

4.3.6 Factors Controlling Soil N_2O Emissions

A stepwise regression analysis was done to examine the factors influencing soil N_2O flux for each of the treatments (**Table 4.6**). Both GWL and WFPS were significant predictors in all treatments. A positive correlation between GWL and N_2O flux was observed for each treatment (T1: R^2 = 0.18; T2: R^2 = 0.20; T3: R^2 = 0.13; T4: R^2 = 0.17), indicating that N_2O flux increased with increased GWL. The highest N_2O flux (2635 μg N m^{-2} hr^{-1}) was also observed in the control plots at a high GWL of −24 cm. An exponential negative correlation was found between WFPS and N_2O emissions for all treatments (T1: R^2 = 0.32; T2: R^2 = 0.30; T3: R^2 = 0.42; T4: R^2 = 0.17). The emissions of N_2O at higher N rates (T3 and T4) were highest at a WFPS of more than 70%. It was observed that the N_2O fluxes increased when WFPS increased from 50% to 70% and decreased afterwards when the WFPS increased to a higher WFPS (> 70%) (**Table 4.7**). A significant positive correlation between NO_3^- concentration and N_2O emissions ($p < 0.01$) and a significant negative correlation between WFPS and NO_3^- ($p < 0.05$) were observed with a WFPS ranging between 70% and 96% (**Table 4.7**). Based on the standardized regression coefficients, the strongest predictor was GWL, except for T2 (**Table 4.6**). Also, the standardized coefficient of GWL was increased from T2 to T4 (**Table 4.6**). Soil N_2O emissions were significantly correlated with both GWL ($p < 0.001$) and WFPS ($p < 0.01$) for all treatments. Soil N_2O emission was significantly correlated with soil temperature for T2 only ($p < 0.01$) while inorganic N was significantly correlated with N_2O emissions for T3 and T4 only ($p < 0.05$) (**Table 4.6**). An exponential positive correlation between N_2O emissions and NO_3^- for T3 (R^2 = 0.23) and T4 (R^2 = 0.12) was observed.

The effect of GWL on N_2O flux for both GWL conditions in 2010 is shown in **Figure 4.5**. The N_2O flux increased to above 800 μg N m^{-2} hr^{-1} with a GWL shallower than −60 cm. A significant positive correlation between N_2O flux and NO_3^- was observed for T4 (R^2 = 0.23) but only at a low GWL of deeper than −60 cm ($p < 0.05$).

Table 4.6 The stepwise regression analysis denoting the effect of environmental variables and soil inorganic N on the N_2O fluxes in each treatment (n = 72).

Treatment	Variable	Std. Coefficient	SE	p-value	R^2
T1	GWL	0.375	1.958	0.000	0.18
	WFPS	−0.374	3.81	0.000	0.32
T2	GWL	0.373	1.659	0.000	0.2
	WFPS	−0.322	3.143	0.002	0.29
	Soil temperature at 5 cm	0.648	52.43	0.003	
	Soil temperature at 10 cm	−0.419	69.2	0.05	
T3	WFPS	−0.415	4.698	0.000	0.42
	GWL	0.454	2.314	0.000	0.13
	NH_4^+	0.235	0.473	0.009	
	NO_3^-	0.222	4.216	0.038	
T4	NO_3^-	0.442	2.645	0.000	0.29
	GWL	0.516	2.253	0.000	0.17
	WFPS	−0.293	4.73	0.002	0.31

Table 4.7 Pearson's correlation between the N_2O emissions and WFPS and NO_3^- concentrations at WFPS of 50%–70% and > 70% (n = 79–207).

	50%–70%		70%–96%	
Variable	N_2O	WFPS	N_2O	WFPS
WFPS	0.384**	-	−0.506**	-
	0.000	-	0.000	-
NO_3^-	0.032	−0.115	0.376**	−0.137*
	0.782	0.313	0.000	0.049

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

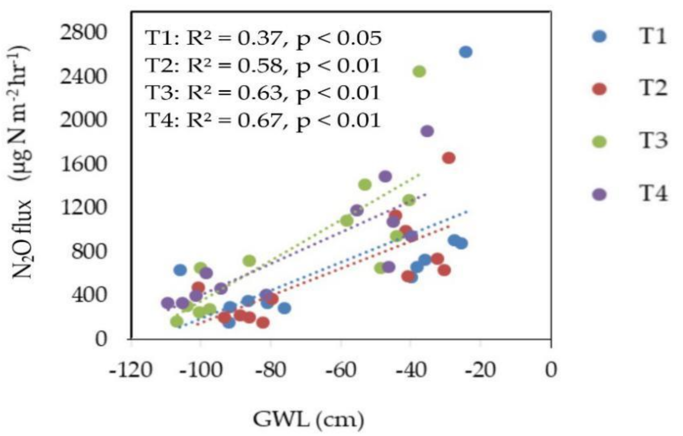

Figure 4.5 Relationship between GWL and N_2O flux for each treatment in 2010.

4.4 Discussion

4.4.1 Effect of N Fertilization on N_2O Emissions

The increase in N_2O flux with a small peak following N fertilization, as generally observed in this study, was also reported in other studies (Weitz et al., 2001; Zhou et al., 2016). In this study, only T4 saw significantly increased annual N_2O emissions. However, a previous incubation study showed that the addition of ammonium sulphate to tropical peatland suppressed N_2O emissions due to high ammonium content and an anaerobic condition that inhibited nitrification (Hadi et al., 2000). However, it was also observed that N_2O fluxes were occasionally higher in control plots compared to N-fertilized plots. It is likely that the greater part of N_2O fluxes from drained organic soil was derived from N released as a result of peat decomposition, and not from fertilization (Takakai et al., 2006; Oktarita et al., 2017; Leifeld et al., 2018), contributing to insignificant effects of N fertilizers on N_2O emissions on tropical peatland. A study on temperate peat showed that N fertilization stimulated N_2O flux only when application rates were very high (480 kg N ha^{-1}) but the N_2O flux hardly increased under 60–120 kg N ha^{-1} application rates even when NO_3^- was high (Augustin et al., 1998). Although the effect of N application on annual cumulative N_2O emissions was only significant in T4, the N application still has the potential to induce annual cumulative N_2O emissions when the N fertilizer goes above 62.2 kg N ha^{-1} yr^{-1}-10% to 96% higher than without N.

The annual N_2O emissions in this study were significantly increased with N fertilization for T4 only in 2010, 2011, 2012, and 2016 (**Table 4.4**). In these years, annual cumulative N_2O emissions were higher, coinciding with higher NO_3^- concentration. In 2010, N fertilization significantly increased both NO_3^- and N_2O emissions but only for T4. This could be due to the short-term drastic GWL change in 2010 in which increased GWL significantly decreased NO_3^- concentration and significantly increased both WFPS and N_2O

emissions (**Table 4.2**). Alternating between low (deeper than −60 cm) and high groundwater level (GWL) (shallower than −60 cm), enhanced nitrification during low GWL further supplied NO_3^- for denitrification in high GWL, contributing to higher N_2O emissions in high GWL (Martikainen et al., 1993; Susilawati et al., 2016). In 2011, higher N_2O and NO_3^- were observed with decreasing GWL in June 2011 to December 2011, implying the occurrence of the nitrification process, which may be the reason for the larger annual N_2O emissions. In 2012, annual N_2O emissions started to significantly reduce for all treatments (**Table 4.4**), possibly due to the palm canopy density and leaf area index (LAI). As the palm grows, the size of its canopy increases and eventually closes (usually 4 years after planting). Canopies with high LAIs can block sunlight from reaching the soil surface and absorb more momentum; therefore, allowing less vertical mixing of air within the canopy (Hardwick et al., 2015). These conditions keep the air and soil beneath the canopy cool during the day, reducing water loss from the soil via evaporation. A higher bulk density and a lower total porosity due to compaction and peat decomposition cause more micropores to form, resulting in increased water retention capacity even during the dry season and the reduction in ground water level (Kurnain, 2016). The increase in WFPS with time may have decreased the N mineralization and nitrification but enhanced denitrification, leading to a reduction in NO_3^- supplies and N_2O emission.

To date, studies investigating the effect of N fertilization on N_2O emissions in tropical peatland have mainly used urea as the N source (Takakai et al., 2006; Sakata et al., 2014, Melling et al., 2007; Oktarita et al., 2017). Urea is widely used as an N fertilizer worldwide due to its lower price per unit N and its high N content (46% N) compared to other N fertilizers. The magnitude of the pH decrease has been found to be greater using ammonium sulfate compared to urea (Fageria et al., 2010). It has been reported that the addition of urea accelerated nitrification while AS tended to lower the nitrification status and inhibited nitrification at higher rates due to increased soil pH as a result of the hydrolysis of urea, which stimulated nitrifier activity and the availability of soluble substrate, thus enhancing the nitrification rate (Ariffin et al., 2015; Tierling and Kuhlman., 2018). However, in the case of paddy fields, application of ammonium sulphate would result in larger emissions of N_2O than that of urea, probably due to the faster availability of NH_4^+-N from AS for faster nitrification and thus, higher N_2O production (Cai et al., 1997; Kumar et al., 2000).

In the current study, annual cumulative N_2O emissions from 2010 until 2012 (ranging from 24.9–79.7 kg N ha^{-1} yr^{-1}) were higher than the values obtained in a previous study involving a urea-fertilized oil palm plantation on tropical peatland (ranging from 12.8–26.6 kg N ha^{-1} yr^{-1}) (Oktarita et al., 2017) while the values from 2013 until 2016 (ranging from 6.5–22.9 kg N ha^{-1} yr^{-1}) fell within the previous study's range. The higher values of N_2O emissions from 2010 until 2012 in this study compared to the previous study may be due to the lower GWL during the period in this study. However, the aforementioned values still fall within the values obtained by studies on cropland on tropical peatland (Takakai et al., 2006) (ranging from 21–259 kg N ha^{-1} yr^{-1}). The EF for T4 in 2010, 2011, 2012, and 2016 was 17.6%, 25.9%, 20.0%, and 2.7%, respectively (**Table 4.5**). In other studies, on oil palm plantation on tropical peatland, the EF of urea and coated urea was 19.1% and 43.8%, respectively (Sakata et al., 2014), higher than the EF values obtained in this study.

4.4.2 Factors Influencing Soil N_2O Emissions

The regression analysis revealed that N_2O fluxes correlated significantly with GWL and WFPS for all treatments, with GWL as the strongest predictor. This result shows that the depth of the water table affects the degree of anaerobicity of the peat, which is essential for denitrification, and the thickness of the aerobic layer, which determines the soil volume for nitrification rate. There was a significant positive correlation between GWL and N_2O flux

($p < 0.001$), where N_2O flux increased as GWL increased. The highest N_2O emissions in the drained tropical peatland forest were found to relate to rising water table conditions during the start of the wet season. After the onset of the wet season, peat moisture increased due to the increased water infiltration and water table accompanied by sufficiently oxic conditions in the surface peat and the increased decomposition of fine root and leaf litter deposited during drier conditions, resulting in a surge in N_2O emissions (Jauhiainen et al., 2012). In 2010, short-term drastic GWL changes were observed and increased GWL significantly increased N_2O emissions by 185% to 253.3% over the low GWL ($p < 0.05$) (**Table 4.2**). Rises in GWL were accompanied by increases in N_2O emissions, through associated increases in WFPS. Peat soil moisture distribution is also influenced by the rate of capillary rise, which, in turn, is affected by GWL and bulk density. The highest soil water content (308%) corresponded to the soil capillary rise in high GWL (−40 cm) and high bulk density (0.2 g cm^{-3}) while the lowest water content (37%) occurred in low GWL (−100 cm) and low bulk density (0.1 g cm^{-3}) (Nugraha et al., 2016). At low GWL (deeper than −60 cm), the WFPS ranged from 50–70% while at high GWL (shallower than −60 cm), the WFPS ranged from 60%–80%. The effect of N fertilization on N_2O emission was prominent in wet soil (Sakata et al., 2014; Li et al., 2005; Liu et al., 2015), which explains the larger effect of GWL on N_2O emissions at high N rates (**Table 4.6**).

After GWL, WFPS was one of the important factors in affecting soil N_2O emissions in this study. The WFPS was negatively correlated with N_2O flux ($p < 0.01$). Soil N_2O emissions increased when WFPS increased from 50% to 70% and decreased when WFPS went above 70%. This phenomenon was observed in the beginning of 2012 where both N_2O flux and NO_3^- decreased in tandem with increased WFPS (> 70%) (**Table 4.7**, **Figures 4.1**). Complete denitrification might have occurred and N_2O was mostly reduced to N_2 when WFPS went above 70% (Davidson et al., 2000; Ishikura et al., 2018). Increasing WFPS likely reduced gas diffusivity in the soil, inhibiting the escape of N_2O and enhancing the probability of its reduction to N_2 (Melling et al., 2007; Smith et al., 1997). Moreover, the low nitrification rate in continuously high WFPS limited the production of NO_3^- for denitrification, leading to low N_2O emissions.

A significant positive correlation between NO_3^- and N_2O flux was only found in T3 and T4 while the effect of NH_4^+ on N_2O flux was only found for T3 (**Table 4.6**). The emissions of N_2O from the soil were better correlated with NO_3^- (product of nitrification and precursor of denitrification) than with NH_4^+, suggesting that denitrification was an important source of soil N_2O in this case (Parn et al., 2018). According to Liu et al. (2007), NH_4^+ enhanced the N_2O flux from the soil only at lower soil moisture, which explains the lack of a relationship between NH_4^+ and N_2O flux when WFPS was mostly higher than 70%. Soil temperature is also considered important in regulating the rate of N_2O flux, as the contributions of nitrification and denitrification to N_2O flux may vary with temperature (Koponen et al., 2006; Lai et al., 2019). For instance, Lai et al. (2019) reported that nitrification and denitrification peaked at 35–40 °C. However, at temperatures above 40 °C, high soil respiration rates will likely decrease oxygen availability, enhancing the anaerobic microsites, leading to the reduced of N_2O to N_2 production. In this study, a significant correlation between soil temperature at 5 cm and 10 cm and soil N_2O flux was only found for T2 (**Table 4.6**). The lack of a relationship between soil temperature and N_2O flux may be due to the constant variation in the soil temperature in tropical regions.

4.4.3 Effect of N Fertilization on Oil Palm Yield

In this study, the N fertilization rates had no effect on annual oil palm yield ($p > 0.05$). Morris et al. (2017) also reported the significant effect of N fertilization on the grain yield of rice plant planted on peat, indicating the existence of a large N pool in the rewetted peat soils, which was also reflected by the higher oil palm yield in the control plot rather than the fertilized plot in the study. A study on the mineral soil in an oil palm plantation showed that N rates of 120 kg N ha^{-1} yr^{-1} met the nitrogen demands (116.2 kg N ha^{-1} yr^{-1}) to produce 30 t ha^{-1} yr^{-1} FFB (Tarmizi and Tayeb, 2006. According to Teh (2016), nutrient demand in oil palm plantations will increase steeply in the next two to four years, after which it will stabilize to a rather constant level (180 kg N ha^{-1}); thus, high soil nutrient levels may not always lead to high nutrient uptake. Annual oil palm yield in this study was negatively correlated with annual cumulative N_2O emissions and NO_3^-($p<0.05$) (**Figure 4.3**), suggesting that increased oil palm yield reduced NO_3^- in soil via N uptake, resulting in lower N_2O emissions. Higher NO_3^- uptake by oil palm in higher WFPS reduced NO_3^- concentration, resulting in decrease of N_2O emission in higher WFPS as indicated by positive relationship between oil palm yield and WFPS ($p<0.001$) (**Figure 4.4**). The effect of plant N uptake on N_2O emissions was also reported by other studies (Simojoki and Jaakkola, 2000; Sosulski et al., 2014). Marwanto et al. (2018) showed that during a drought, two tropical peatlands exhibited a low soil pH (pH 3.7–pH 4.0) at a depth of 50 cm and a high soil pH (pH 5.9–pH 6.8) at a depth of 200 cm. These phenomena are attributed to oxidation reactions such as organic acids and NO_3^- generation in shallower soil and reduction reactions such as denitrification in deeper soil during a drought. Therefore, in the rainy season, when NO_3 leaches and ground water level rises, N_2O production in subsurface soil will be increased. Kusa et al. (2008) also found that the subsurface soil with a shallower ground water level would produce higher N_2O due to NO_3^- leaching.

4.5 Conclusions

Although the effect of N application on annual cumulative N_2O emissions was only significant for T4, N application still has the potential to induce annual cumulative N_2O emissions when more than 62.2 kg N ha^{-1} yr^{-1} N fertilizer rate is applied. Both GWL (p < 0.001) and WFPS (p < 0.01) were significant predictors for all treatments in which the effect of GWL on N_2O flux increased as the N rates increased. Based on this relationship, denitrification was the dominant source of N_2O emissions in this study. Alternating between low and high GWL, particularly in 2010–2011, enhanced nitrification during low GWL further supplied NO_3^- for denitrification in the high GWL, contributing to higher N_2O fluxes in the aforementioned years. Increasing WFPS (>70%) was observed to start in 2012 correlating to a decrease in both N_2O flux and NO_3^-, which could be due to complete denitrification, a reduction in gas diffusivity, and plant N uptake. This study suggests that higher WFPS is better to increase yield and decrease N_2O emission as the palms getting mature. Thus, the effect of plant uptake on N_2O flux should not be undermined, at least until the completion of the planting cycle.

CHAPTER 5

Effect of Ground Water Level Control and N Fertilization on CO_2 Fluxes from Oil Palm Plantation on Tropical Peatland

5.1 Introduction

Tropical peat swamp forests is largely composed of coarse woody material from fallen trees, branches, and dead roots which develop under conditions of near continuous soil saturation that leads to anaerobic conditions which dramatically slows decomposition. Thus, tropical peat swamp forests are seen to be an important role in the global carbon (C) cycle and has contribution to climate change. Today, tropical peat swamp forest has been developed and mostly used for agricultural activities. In Malaysia and Indonesia, tropical peatland is used for oil palm cultivation as oil palm is the security crop for both countries.

The expansion of oil palm plantation into tropical peatland has attracted considerable attention especially on the greenhouse gases emissions due to its effect on global warming. The conversion of tropical peat swamp forest into oil palm plantation requires drainage which typically accelerates the rate of peat mineralization and enhances soil CO_2 emissions to the atmosphere (Page et al., 2011; van Huissteden et al., 2006; Hooijer et al., 2010). Other agriculture management such as nitrogen (N) fertilization was reported could affects the soil C status by affecting the crop biomass and microbial decomposition (Green et al., 1995). Several studies on the effects of the N fertilizer on soil CO_2 fluxes from mineral soils revealed varied results. Increased of N fertilization increased the nutrient status, plant biomass and belowground carbon input via root exudates and turnover, resulting in higher CO_2 emissions due to higher microbial activities and biomass (Lee and Jose, 2003). However, other study reported that the addition of N significantly depresses microbial communities due to accumulation of toxic NH_4^+, resulting in decreased soil CO_2 emissions (Bowden et al., 2004).

Most studies reported that lowering of ground water level (GWL) accelerated peat decomposition and released higher CO_2 emissions (Ishikura et al., 2017; Wakhid et al., 2017; Itoh et al., 2017). However, water-filled pore space (WFPS) was reported to be more dominant in affecting soil CO_2 emissions in peat compare to GWL because drainage and compaction could increase bulk density and decrease total porosity of peat, resulting in higher WFPS (Melling et al., 2005). Soil temperature was positively affected soil CO_2 flux in open peat areas (Schrier-Uijl et al., 2013; Jauhiainen et al., 2014). The occurrence of both rise of temperature and lower GWL at the same time increased soil CO_2 fluxes in peat (Silvola et al., 1996). However, Hirano et al. (2014) found that the effect of soil temperature rise on soil CO_2 efflux was small even at an open peatland when GWL was low. Some studies indicated that temperature had no effect on CO_2 flux due to constant temperature in tropics (Adachi et al., 2006; Wakhid et al., 2017). Relative humidity as one of the important factors in affecting CO_2 emissions in tropical peatland was reported by Melling et al. (2005) which indicated that optimum relative humidity for high CO_2 flux was between 73 and 85%. Soil chemical properties such as soil pH (Ishikura et al., 2017; Ishikura et al., 2018) and carbon to nitrogen (C/N) ratio (Swails et al., 2017) also found to affect soil CO_2 emissions from tropical peatland. Soil CO_2 fluxes showed significant positive correlation with the N_2O flux, which indicated that soil organic matter decomposition was closely related to the N_2O production (Kimura et al., 2012; Mu et al., 2014).

Few recent studies evaluated the effect of N fertilizer on CO_2 emissions in tropical peatlands found that fertilizer had no significant effect on CO_2 emissions (Sakata et al., 2014; Watanabe et al., 2009). However, other study by Jauhiainen et al. (2014) observed an increase in CO_2 flux from agricultural land and a decrease from degraded land after N fertilizer application. A review paper showed that CO_2 emission was significantly higher in tropical peatland than northern boreal and temperate peatlands, and increased with N fertilization significantly (Hatano, 2019). However, few of these studies are long term studies where environmental conditions and peat characteristics with time could display a different response of soil respiration to N addition. While effects of N fertilizers from cultivated tropical peatland are still limited, the understanding of this subject is essential to develop the mitigation approach for sustainable management of tropical peatland for agriculture. Therefore, long term studies on the effect of N fertilization on soil CO_2 fluxes was conducted to quantify the annual soil CO_2 emissions from an oil palm plantation on a tropical peat soil from different N rates, to identify the regulatory factors affecting soil CO_2 fluxes over time and to understand the temporal effect of GWL on CO_2 fluxes.

5.2 Materials and Methods

Soil CO_2 is released from the soil through soil respiration, which includes three biological processes, namely microbial respiration, root respiration and faunal respiration (Rastogi et al., 2002; Kuzyakov, 2006). As described in Chapter 3, monthly measurement of CO_2 fluxes was done using closed chamber method in an oil palm plantation (*Elaeis guineensis* Jacq.) located in a tropical peatland in Sarawak, Malaysia from January 2010 to December 2013 and resumed from January 2016 to December 2017. Four different N rates were involved; control (T1, without N fertilization), low N (T2, 31.1 kg N ha^{-1}), moderate N (T3, 62.2 kg N ha^{-1}), and high N (T4, 124.3 kg N ha^{-1}) in three blocks (three replications). Gas emissions in the field were collected between 9 a.m. and 11 a.m. Environmental variables such as air temperature, relative humidity, soil temperature at 5 cm, groundwater level, and rainfall were measured. Upon completing the gas measurement, the bulk density, water-filled pore space (WFPS), total porosity of the soil inside the chamber were assessed by collecting soil core samples using a core ring (5 cm diameter, 5.1 cm height). Soil was collected at 0-25 cm depth using peat auger for soil pH, nitrate (NO_3^-), sulphate (SO_4^{2-}), ammonium (NH_4^+), loss on ignition (LOI), carbon (C), nitrogen (N). Two-way ANOVA was performed to examine the annual cumulative CO_2 emissions and year among treatments. Tukey's HSD was used to compare the mean difference ($p < 0.05$) of the given variable across the treatments. Correlation between CO_2 fluxes, environmental variables and soil properties was assessed using the Pearson's correlation coefficient. A stepwise multiple regression analysis was conducted to identify the main factors influencing CO_2 fluxes as well as the environmental parameters and soil properties for each treatment.

5.3 Results

5.3.1 Soil CO_2 Fluxes and Annual Cumulative CO_2 emissions

As shown in **Figure 5.1**, soil CO_2 fluxes varied from 34.6 to 333.6 mg C m^{-2} h^{-1} for T1, 29.5 to 429.2 mg C m^{-2} h^{-1} for T2, 3.2 to 441.4 mg C m^{-2} h^{-1} for T3 and 24.9 to 438.0 mg C m^{-2} h^{-1} for T4. Monthly variation in CO_2 fluxes were not significantly affected ($p>0.05$) by the N fertilization over the study period except for January 2013, February 2016, July 2016 and September 2017. Only CO_2 flux from T3 was significantly higher than control in January 2013 ($p<0.05$) and September 2017 ($p<0.05$). In February 2016, CO_2 fluxes from both T3 and T4 were significantly lower than control ($p<0.01$). In July 2016, only CO_2 flux from T4 was significantly lower than control ($p<0.05$). Higher CO_2 fluxes ranged from 172 to 309.8 mg C m^{-2} hr^{-1} were occurred when GWL lowered from -80.9 to -103.4 cm in January 2010 to June 2010. Rising of GWL afterwards reduced soil CO_2 fluxes in all treatments. In this study, increased of CO_2 fluxes were observed during dry season when GWL dropped but it was also found that increased soil CO_2 fluxes may possibly happened when GWL increased during wet season. It was observed that sudden increase of CO_2 fluxes between October

2012 to January 2013 was found in accordance to simultaneous increased in GWL and WFPS in wet season. It was observed that sudden increase of CO_2 fluxes between October 2012 to January 2013 in wet season.

Application of N fertilizer had no significant effect on annual cumulative CO_2 emissions in each year (p=0.448) (**Table 5.1**). Annual cumulative CO_2 emissions ranged from 7.7 to 16.6 t C ha^{-1} yr^{-1} for T1, 9.8 to 14.8 t C ha^{-1} yr^{-1} for T2, 10.5 to 16.8 t C ha^{-1} yr^{-1} for T3 and 10.4 to 17.1 t C ha^{-1} yr^{-1} for T4. Annual cumulative CO_2 emissions in all treatments were decreased with time with the lowest value was recorded in year 2017 and highest in 2010 in T1, T2 and T3.

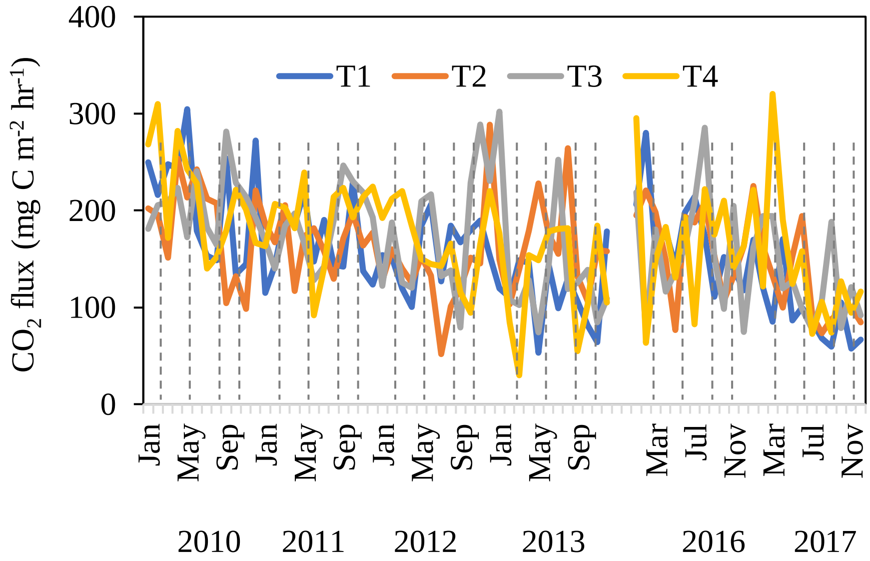

Figure 5.1 Monthly variation of CO_2 fluxes of each treatment (2010-2017). Dash line indicates N fertilization (every March, June, September and November annually).

Table 5.1 Annual cumulative CO_2 emissions (t C ha^{-1} yr^{-1}) for each of treatment (n=3).

Year	**T1**	**T2**	**T3**	**T4**
2010	16.6±1.0$^{a\ A}$	14.8±1.4$^{a\ A}$	16.8±0.6$^{a\ A}$	17.1±3.9$^{a\ A}$
2011	13.5±1.6$^{a\ B}$	13.4±0.5$^{a\ AB}$	14.7±2.4$^{a\ AB}$	15.3±3.5$^{a\ A}$
2012	12.9±0.6$^{a\ B}$	10.9±1.5$^{a\ AB}$	13.9±3.7$^{a\ AB}$	13.2±2.5$^{a\ A}$
2013	8.9±0.6$^{a\ C}$	13.0±2.4$^{a\ AB}$	10.7±1.0$^{a\ B}$	10.4±1.8$^{a\ A}$
2016	14.0±1.2$^{a\ AB}$	13.2±2.6$^{a\ AB}$	13.0±1.5$^{a\ AB}$	13.0±0.2$^{a\ A}$
2017	7.7±1.2$^{a\ C}$	9.8±0.5$^{a\ B}$	10.5±1.8$^{a\ B}$	11.4±3.7$^{a\ A}$
Mean	12.3±1.0^{a}	12.5±1.5^{a}	13.2±1.8^{a}	13.4±2.6^{a}
ANOVA				
Source	df	Mean Square	F	p-value
N rates	3	5.499	1.291	0.288
Year	5	66.179	15.540	0.000
Year * N rates	15	4.365	1.025	0.448
Error	48	4.259		

The letters (a, b, c) in the row indicate a significant difference between treatments while the letters (A, B, C) in the column indicate a significant difference between years using Tukey's Test at $p < 0.05$.

5.3.2 Environmental Variables and Soil Properties

As shown in **Figure 5.2 (a)**, clear seasonal pattern of rainfall and GWL were observed. During dry season (May to September), rainfall ranged from 37 to 389 mm while during wet season (November to March), rainfall ranged from 144 to 482 mm. The highest and lowest total rainfall during wet season was in year 2010 (1681 mm) and 2017 (939 mm), respectively. The highest total rainfall during dry season was recorded in year 2010 (1342 mm) and the lowest was in year 2016 (469 mm). In this study, ground water level (GWL) were below peat surface throughout the year, ranging from -103.4 to -31.5 cm. Due to poor water table management by the plantation, the GWL was very low ranged from -80.9 to -103.4 cm from January 2010 to June 2010. However, upon recommendation for best management practice, the raising of GWL was done in July 2010. The lowest GWL in each year mostly occurred during dry season. As shown in **Table 5.2**, there was no significant differences among treatments for GWL (p=0.062).

WFPS patterns were clearly affected by variation of GWL in year 2010 to 2011 (**Figure 5.2 (a) and (b)**). The WFPS in all treatments dropped in September 2011 coincided with lowering of GWL. It was observed that increased of WFPS and GWL between October 2012 to January 2013 in wet season were coincided with increase of CO_2 fluxes during the same period (**Figure 5.1**). The WFPS ranged for T1 was from 54.2 to 95.9%, T2 was from 51.9 to 92.9%, T3 was from 56.7 to 93.5% and T4 was from 54.2 to 93.3%. There were no significant differences of WFPS among treatments (p=0.982) (**Table 5.2**).

Monthly variation of bulk density and soil porosity are shown in **Figure 5.2 (c) and (d).** It was observed that bulk density increased while soil porosity with time in all treatments. Bulk density varied from 0.20 to 0.27 g cm^{-3} during the period of this study and no statistically significant differences among treatments ($p<0.05$) (**Table 5.2**). Soil porosity ranged from 78.3 to 88.5, 78.5 to 89.0, 78.1 to 90.2 and 77.7 to 88.9 for T1, T2, T3 and T4, respectively. There were no significant differences in soil porosity among treatments ($p=0.857$) (**Table 5.2**).

Monthly air temperatures, relative humidity and soil temperatures are shown in **Figure 5.2 (e), (f) and (g).** It was observed that air temperatures decreased with time with the minimum air temperature was 26°C and maximum was 39.1°C. Relative humidity which opposite with air temperature was increasing with time, ranging from 49 to 96%. Soil temperatures measured at 5 cm depth was also decreasing with time in all treatments, with the minimum and maximum values were 25.8 and 30.9 °C, respectively.

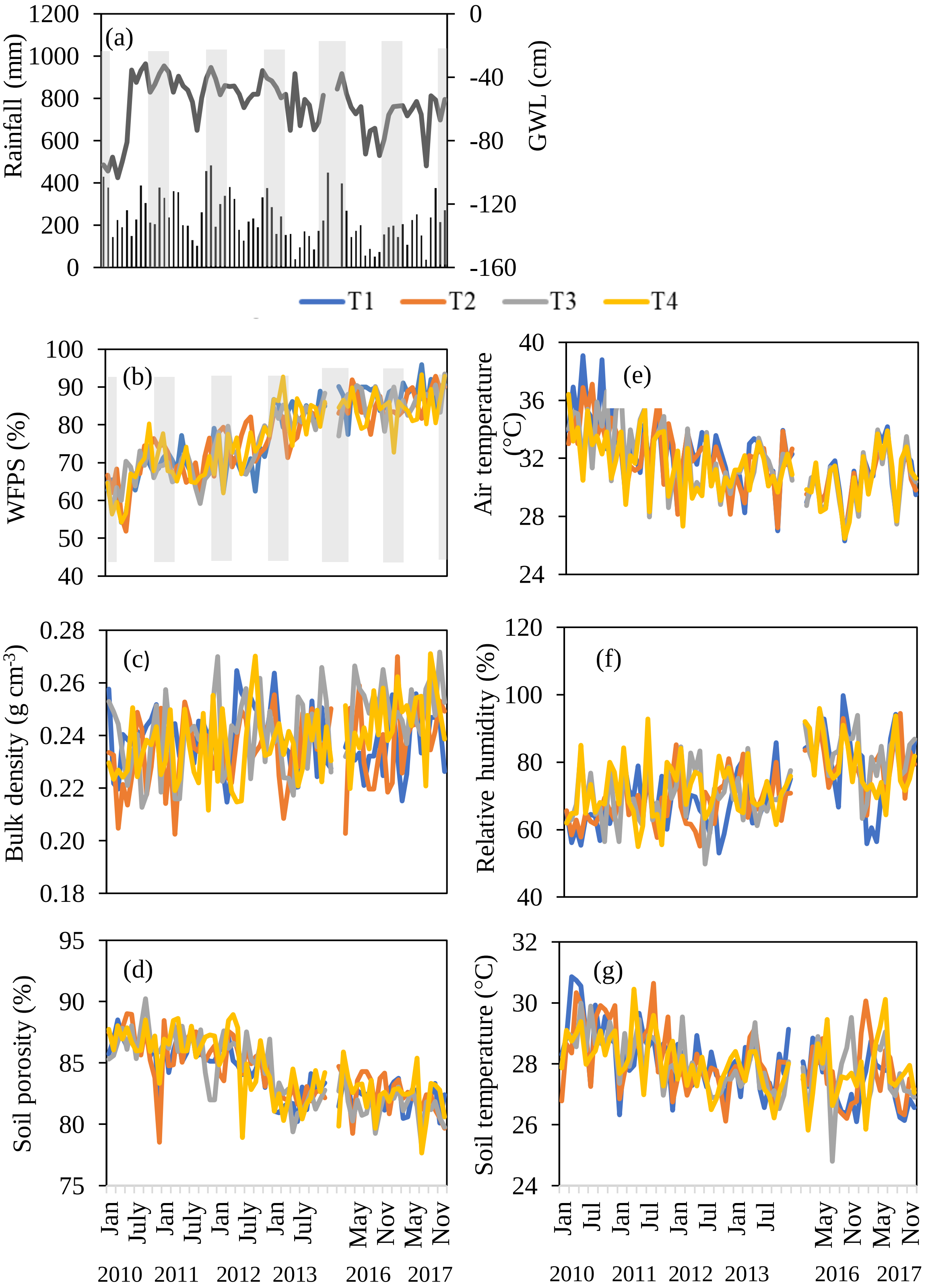

Figure 5.2 Monthly variation of (a) rainfall, GWL, (b) WFPS (c) bulk density, (d) soil porosity, (e) air temperatures, (f) relative humidity and (g) soil temperatures of each treatment (2010-2017). Gray box indicates wet season (November – March).

As shown in **Figure 5.3 (a)**, the variations of NH_4^+ ranged from 253 to 865.2, 263 to 785.7, 253 to 641.5 and 171 to 651.6 mg N kg-1 for T1, T2, T3 and T4, respectively while soil NO_3^- varied from 1.1 to 41.9, 1.0 to 52.0, 1.8 to 44.5 and 1.5 to 81.1 mg N kg^{-1} for T1, T2, T3 and T4, respectively (**Figure 5.3 (b)**). As shown in **Table 5.2**, there were no significant differences among treatments for both soil NH_4^+ ($p=0.185$) and NO_3^- ($p=0.152$). Soil pH for T1, T2, T3 and T4 ranged from 3.12 to 3.67, 3.14 to 3.71, 2.99 to 3.56 and 2.90 to 3.67, respectively (**Figure 5.3 (c)**) with T3 and T4 were significantly lower than T1 (control) ($p<0.001$) but T2 did not differ significantly from T1 (control) ($p=0.785$) (**Table 5.2**). As shown in **Figure 5.3 (d)**, highest monthly SO_4^{2-} contents were observed mostly in T4, ranging from 1.3 to 1505.7 mg S kg^{-1} while range of SO_4^{2-} in T1, T2 and T3 were from 0.8 to 675.3, 1.2 to 598.4 and 0.7 to 592.0 mg S kg^{-1}, respectively (**Figure 5.3 (d)**). Only T4 had significantly increased SO_4^{2-} ($p<0.001$) (**Table 5.2**). There were no significant differences among treatments in C/N ratio ($p=0.486$) (**Table 5.2**), with monthly variation ranged from 19.7 to 35.9 (**Figure 5.3 (e)).** Range of LOI was from 84 to 98.3% for LOI **and (Figure 5.3 f)**) with only T2 was significantly higher than control ($p<0.01$) (**Table 5.2**).

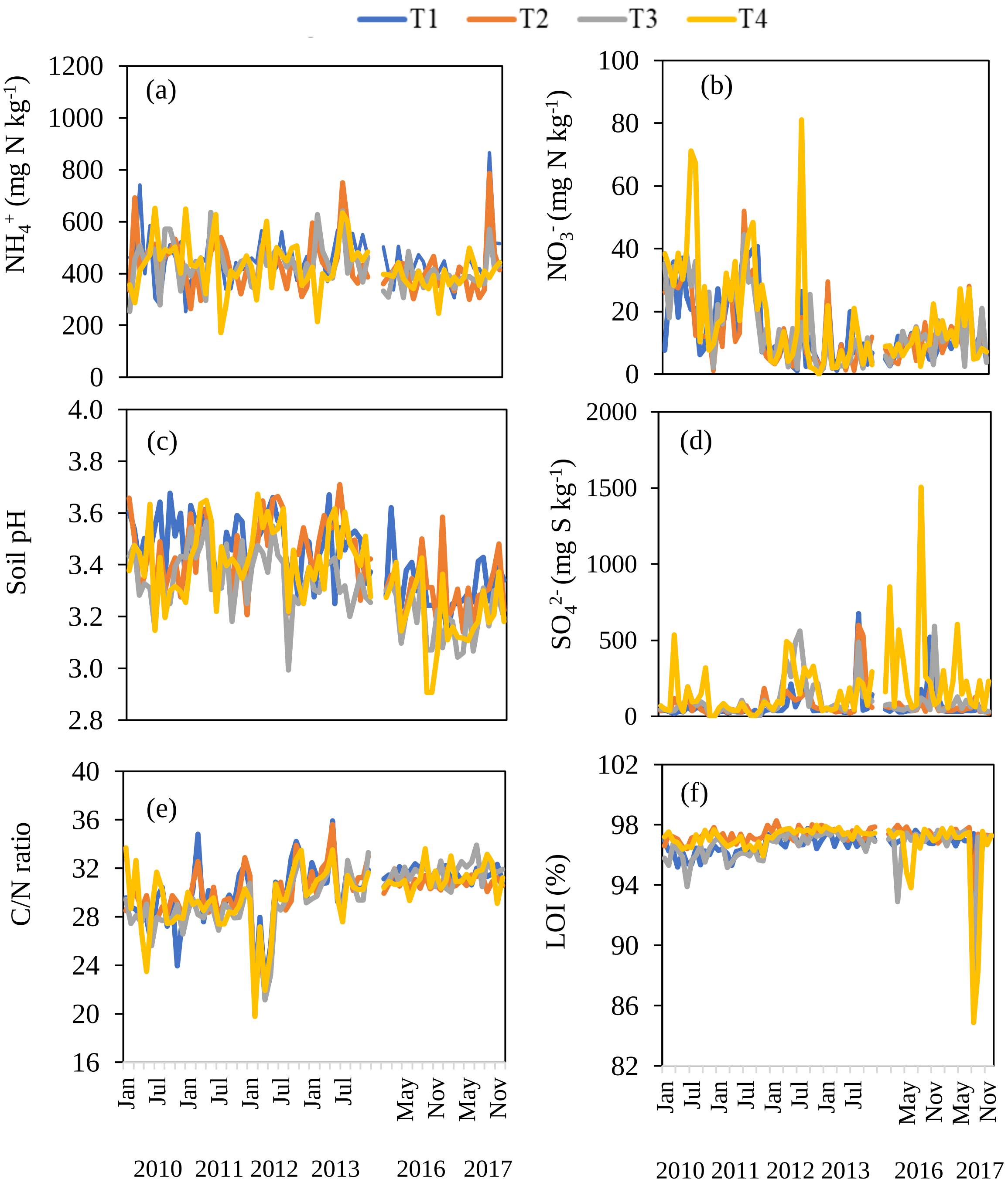

Figure 5.3 Monthly variation of (a) NH_4^+-N, (b) NO_3^--N, (c) soil pH, (d) SO_4^{2-}-S, (e) C/N ratio and (f) LOI of each treatment (2010-2017).

Table 5.2 Soil physico-chemical properties from each treatment plots during study period (n=72).

Variables	T1	T2	T3	T4
GWL (cm)	-53.2 (20.2)	-54.4 (17.3)	-60.7 (17.0)	-60.6 (17.4)
WFPS (%)	77.4 (10.4)	77.3 (8.9)	77.2 (9.4)	76.8 (9.5)
Bulk density (g cm^{-3})	0.25 (0.01)^{ab}	0.24 (0.01)^{b}	0.25 (0.01)^{b}	0.24 (0.02)^{a}
Soil porosity (%)	83.9 (2.4)	84.1 (2.4)	83.9 (2.8)	84.2 (3.2)
NH_4^+ (mg N kg^{-1})	453.8 (95.8)	429.5 (94.9)	427.0 (79.5)	423.3 (91.8)
NO_3^- (mg N kg^{-1})	13.5 (10.6)	13.0 (10.2)	14.5 (10.8)	17.1 (16.7)
Soil pH	3.43 (0.1)^{a}	3.41 (0.1)^{ab}	3.30 (0.1)^{c}	3.36 (0.2)^{bc}
SO_4^{2-} (mg S kg^{-1})	65.7 (100.1)^{b}	76.3 (93.8)^{b}	104.9 (124.9)^{b}	182.2 (226.6)^{a}
C/N ratio	30.3 (2.4)	30.0 (2.3)	29.7 (2.5)	29.8 (2.6)
LOI (%)	96.7 (1.0)^{b}	97.3 (0.6)^{a}	96.6 (1.6)^{b}	96.9 (1.9)^{ab}

Significant differences ($P < 0.05$) by fertilization treatments were labelled with different letters across rows. Data were mean (SD).

5.3.3 Regulating Factors of Soil CO_2 Fluxes

As shown in **Table 5.3**, CO_2 fluxes from T1 had significant correlation with N_2O fluxes, oil palm yield, rainfall, soil porosity, WFPS, air temperature, relative humidity, soil temperature and soil pH. In T2, CO_2 fluxes was significantly correlated with N_2O fluxes, WFPS, air temperature, relative humidity and soil temperature. In T3, significant correlation was found between CO_2 fluxes and N_2O fluxes, oil palm yield, WFPS, soil porosity, air temperature, soil pH, NO_3^--N, and C/N ratio. Fluxes of CO_2 from T4 had significant correlation with N_2O fluxes, oil palm yield, soil porosity, WFPS, GWL, soil temperature and C/N ratio. Overall, CO_2 fluxes were positively correlated with N_2O fluxes, rainfall, soil porosity, air temperature, soil temperature, soil pH, and NO_3^--N while negative correlations were obtained between CO_2 fluxes and oil palm yield, WFPS, GWL, relative humidity and C/N ratio. From these results, stepwise multiple regression analysis for CO_2 flux was done using N_2O fluxes, oil palm yield, rainfall, WFPS, GWL, porosity, air temperature, relative humidity, soil temperature, pH, NO_3^--N and C/N ratio (**Table 5.4**). The results show that CO_2 flux was negatively correlated with WFPS in all treatments ($p<0.001$). By using the overall data, CO_2 flux showed significantly positive correlation with both WFPS ($p<0.001$) and N_2O fluxes ($p<0.05$) with WFPS as the strongest predictor. WFPS as dominant factor in affecting soil CO_2 fluxes was influenced by soil porosity, as indicated by negative linear relationship between soil porosity and WFPS ($p<0.001$) (**Figure 5.4(a)**) and positive linear relationship between soil porosity and CO_2 fluxes ($p<0.001$) (**Figure 5.4(b)**). It was found that soil porosity was influenced by bulk density as indicated by their negative linear relationship ($p<0.001$) (**Figure 5.4(c)**).

Table 5.3 Pearson's correlation coefficients between CO_2, N_2O, oil palm yield, environmental variables and soil properties.

Variables	T1	T2	T3	T4	All
N_2O	0.15*	0.15*	0.27**	0.21**	0.22**
Oil palm yield	-0.27**	-0.007	-0.14*	-0.19**	-0.149**
Rainfall	0.17*	0.003	0.11	0.06	0.09*
GWL	-0.03	-0.01	-0.04	-0.16*	-0.07*
Bulk density	0.10	0.05	0.04	0.01	0.05
Porosity	0.26**	0.10	0.17*	0.19**	0.18**
WFPS	-0.44**	-0.35**	-0.33**	-0.41**	-0.38**
Air temperature	0.21**	0.22**	0.13*	0.12	0.16**
Relative humidity	-0.18**	-0.22**	-0.13	-0.09	-0.14**
Soil temperature	0.22**	0.22**	0.06	0.25**	0.18**
NH_4^+-N	-0.07	-0.01	-0.04	-0.02	-0.04
NO_3^--N	0.13	0.07	0.16*	0.08	0.11**
Soil pH	0.18**	0.12	0.18**	0.06	0.10**
SO_4^--S	-0.07	-0.12	-0.09	0.01	-0.02
C/N ratio	-0.12	0.05	-0.20**	-0.23**	-0.14**
LOI	-0.01	0.04	-0.01	0.09	0.03

Significance at *$p<0.05$ and **$p<0.01$

Table 5.4 Stepwise regression analysis between soil CO_2 fluxes by using rainfall, oil palm yield, WFPS, GWL, porosity, air temperature, relative humidity, soil temperature, pH, NO_3^--N and C/N ratio.

Treatment	Variable	Coefficients	Std. Coefficients	Std. Error	R^2	p-value
T1	Intercept	346.39		33.42	0.15	0.000
(n=202)	WFPS	-2.5	-0.39	0.42		0.000
T2	Intercept	368.36		40.87	0.11	0.000
(n=212)	WFPS	-2.72	-0.34	0.52		0.000
T3	Intercept	389.85		47.98	0.1	0.000
(n=197)	WFPS	-2.89	-0.32	0.61		0.000
T4	Intercept	406.25		46.15	0.12	0.000
(n=203)	WFPS	-3.11	-0.34	0.58		0.000
All	Intercept	342.41		25.02	0.13	0.000
(n=783)	WFPS	-2.46	-0.3	0.3		0.000
	N_2O	0.02	0.11	0.01		0.003

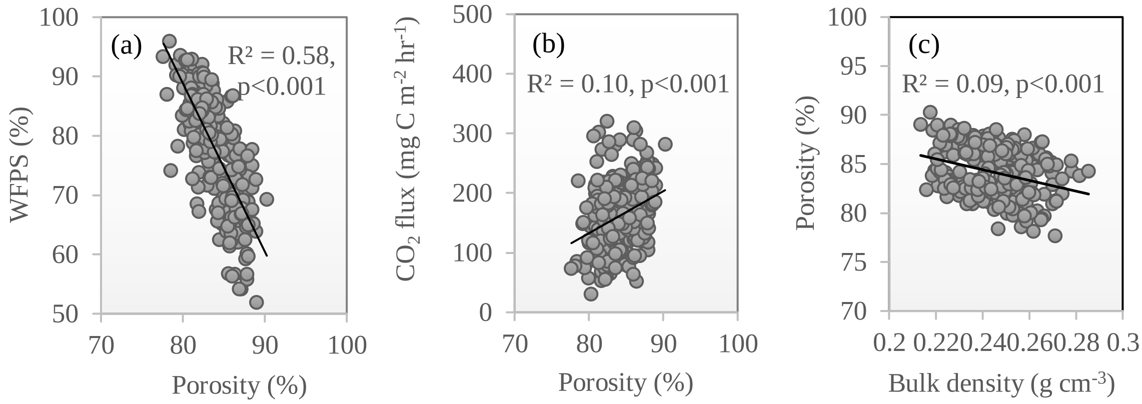

Figure 5.4 Relationship between (a) soil porosity and WFPS, (b) soil porosity and CO_2 fluxes and (c) bulk density and soil porosity.

5.3.4 Temporal Effect of GWL on WFPS and CO_2 Fluxes

As shown in **Figure 5.5**, negative linear relationship between GWL and CO_2 fluxes was found only in year 2010 ($p<0.001$) and 2011 ($p<0.05$), which was 2 and 3-year old palm, respectively, the young stage of oil palm plantation. This concurred with positive linear relationship between GWL and WFPS only in year 2010 and 2011 ($p<0.001$) (**Figure 5.6)**, indicating that GWL had no significant effects on both WFPS and CO_2 fluxes as the palms grew older. However, negative linear relationship was obtained between WFPS and CO_2 fluxes in all age of palms except for 2012 (**Figure 5.7**).

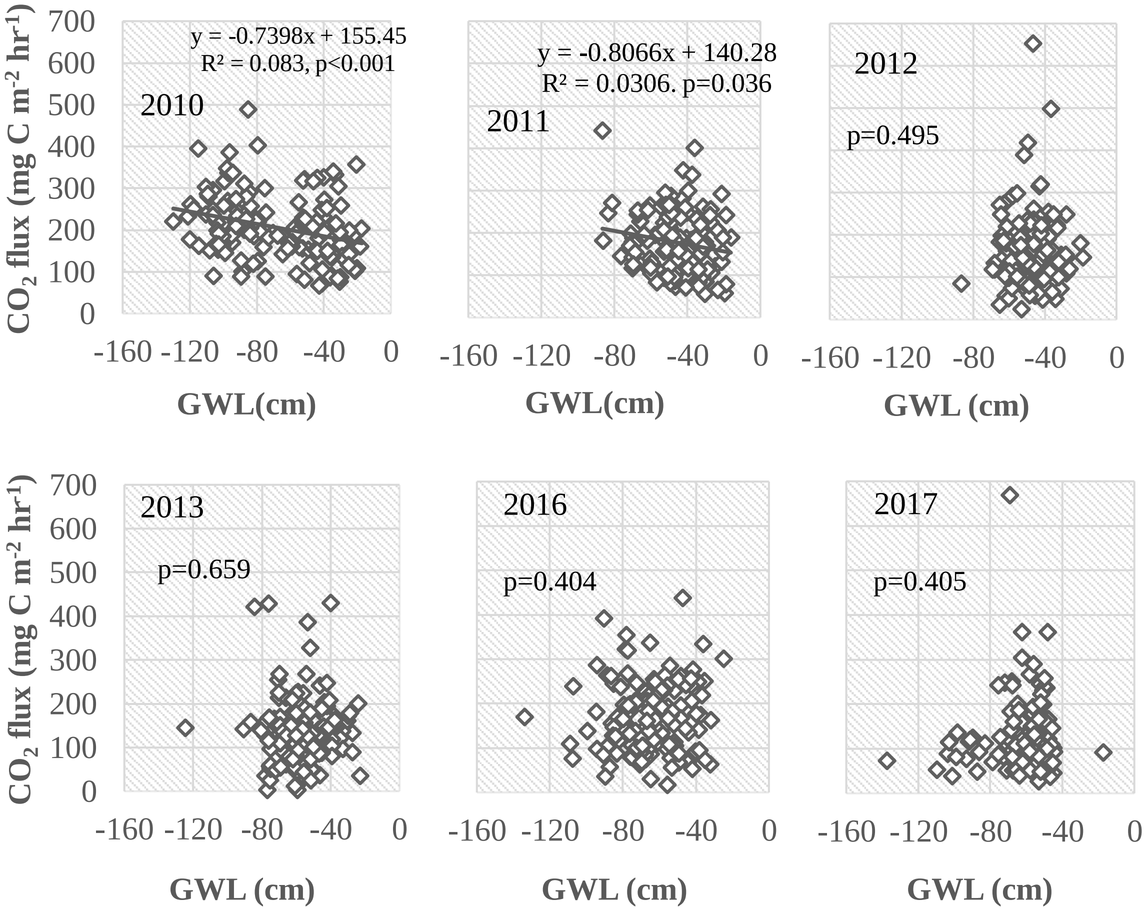

Figure 5.5 Relationship between GWL and CO_2 fluxes in with time (2010-2017).

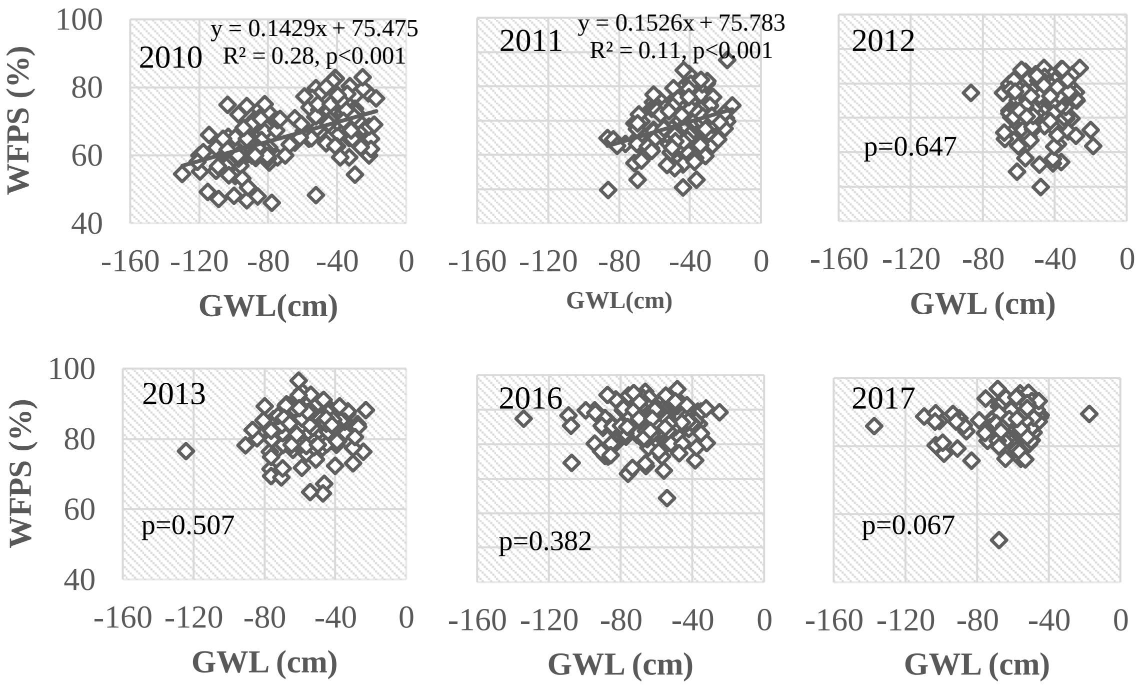

Figure 5.6 Relationship between GWL and WFPS with time (2010-2017).

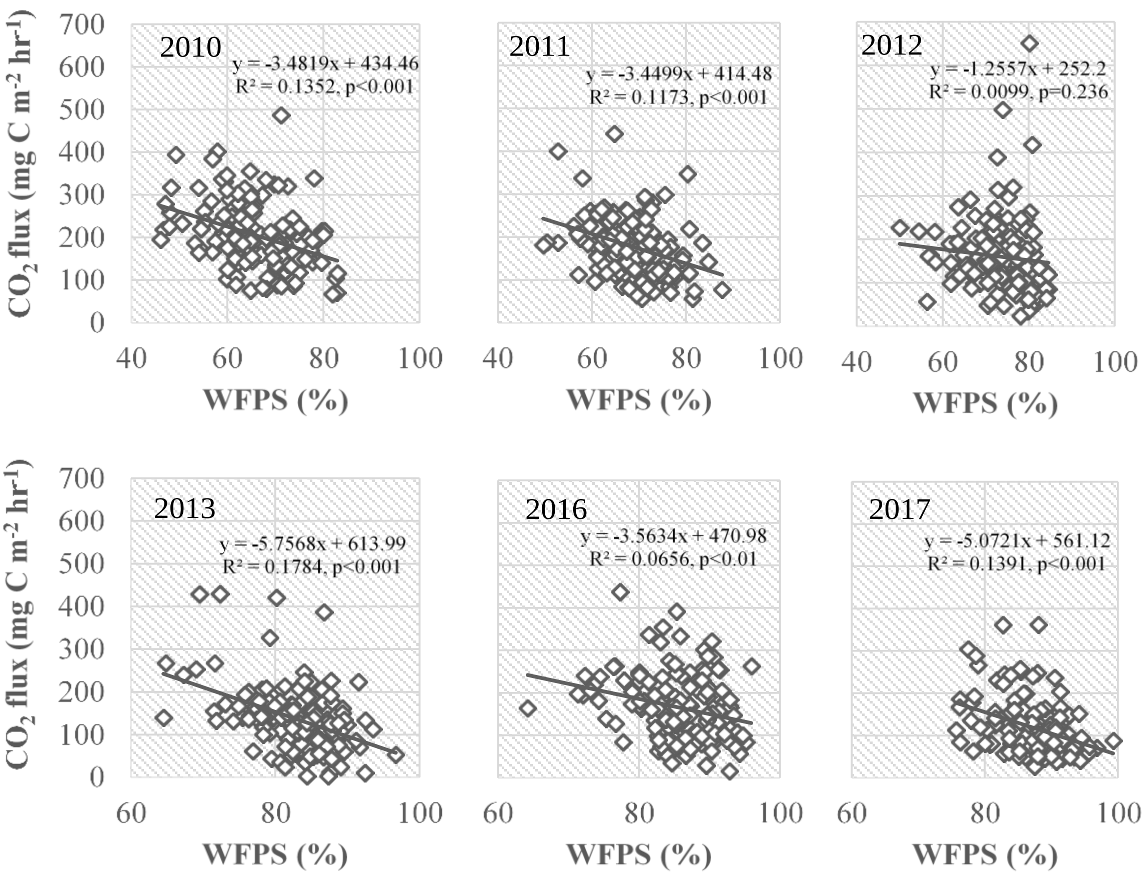

Figure 5.7 Relationship between WFPS and CO_2 fluxes with time (2010-2017).

5.3.5 Effects of N Fertilization on the Relationship of WFPS, CO_2 and N_2O emissions

In **Figure 5.8 (a**), negative relationship between WFPS and CO_2 fluxes were found in all treatments ($p<0.001$) where slope of the CO_2 flux to the WFPS was steeper in T4 (CO_2= -3.18WFPS+414.4, R^2=0.26, $p<0.001$) than other treatments (T1: CO_2= -2.62WFPS+356.8, R^2=0.24, $p<0.001$; T2: CO_2=-2.04WFPS+318.4, R^2=0.20, $p<0.001$; T3: CO_2=-2.65WFPS+370.0, R^2=0.19, $p<0.001$), indicating that CO_2 flux change with the WFPS change was greater in T4 than T1, T2 and T3. Annual cumulative N_2O emissions from Chaddy et al. (2019) was used to check the relationship between CO_2 emissions and N_2O emissions. As shown in **Figure 5.8 (b)**, positive linear relationship was found between annual cumulative CO_2 emissions and annual cumulative N_2O emissions ($p<0.05$), reflecting that N_2O emissions increased with increased of CO_2 emissions by peat decomposition. Slope of the N_2O emissions to the CO_2 emission was steeper in T3 (N_2O=0.005CO_2-0.0382, R^2=0.39, $p<0.01$) and T4 (N_2O=0.005CO_2-0.0246, R^2=0.37, $p<0.01$) than T1 (N_2O=0.003CO_2-0.0107, R^2=0.29, $p<0.05$) and T2 (N_2O=0.003CO_2-0.0165, R^2=0.25, $p<0.05$). This showed that changes of N_2O emissions with the changes of CO_2 emissions was higher in T3 and T4 than T1 and T2.

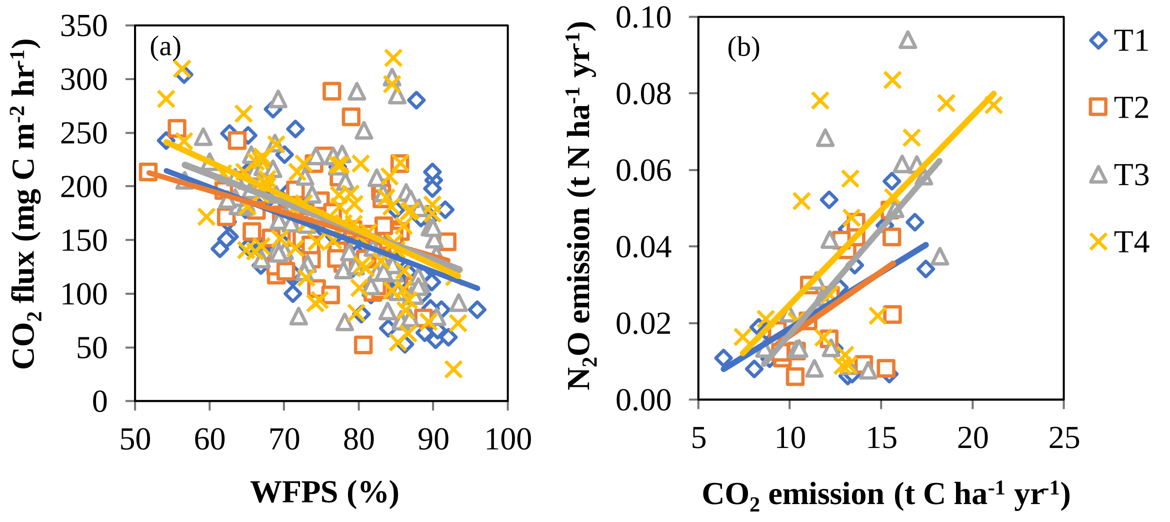

Figure 5.8 Linear relationship between (a) WFPS and CO_2 fluxes and (b) annual cumulative CO_2 emissions and annual cumulative N_2O emissions (Chaddy et al., 2019).

5.4 Discussions

5.4.1 Effect of N Fertilization on CO_2 Fluxes

There was no significant effect of N fertilization on annual cumulative CO_2 emissions ($p=0.448$) (**Table 5.1**). This finding is consistent with previous studies that observed N fertilization had no significant effect on CO_2 fluxes from sago palm cultivation (Watanabe et al., 2009) and 4 year-old oil palm plantation (Sakata et al., 2014). Comeau et al. (2016) found that soil respiration was greater in the fertilized than in the non-fertilized plots after the first fertilization but no enhancement was observed after the second fertilization. As shown by Melling (2016), C/N ratio (28.2 to 31.7) in tropical peat swamp forest in Sarawak prior to conversion was high. However, during early conversion, drainage and dropped of GWL exposed peat to oxic conditions increased rate of peat decomposition and N mineralization, which explain lower C/N ratio in early stage of oil palm plantation in this study (**Figure 5.3(e)**). Soil organic matter with C/N ratios greater than 20 typically requires additional N to support decomposition (Snyder et al., 2009). With N fertilizer application, lower peat C/N ratios were expected in an oil palm plantation but C/N ratio in this study was generally still high (>20) (**Figure 5.3(e)**), which explained the insignificant effects of N fertilization on CO_2 emissions in this study. Due to rapid peat decomposition and lack of added fresh organic matter, peat soils exposed to aerobic conditions during a long period and the organic matter remaining might be recalcitrant to further breakdown, causing increased in recalcitrant carbon with time than labile carbon which reduces decomposition rates (Swails et al., 2017, Könönen et al., 2016). A study at the laboratory incubation scale using tropical peat soil also showed that adding labile C and N enhanced heterotrophic CO_2 production more than only addition of N (Jauhiainen et al., 2016). However, effect of N fertilization on CO_2 emissions should not be ignored as there are many sources of CO_2 fluxes from soil such as microbial respiration of soil organic matter, and plant residue (Kuzyakov,

2006) which are not measured in this study. The response of each components of soil CO_2 fluxes to N fertilization would be different. For instance, in January 2016 and September 2017, only CO_2 flux from T3 was significantly higher than control while in February 2016, CO_2 fluxes from T3 and T4 were significantly lower than control. In July 2016, only CO_2 flux from T4 was significantly lower than control. These indicate that the usage of ammonium sulphate at 62.2 kg N ha^{-1} yr^{-1} as threshold had the potential to increase or reduce CO_2 fluxes. Other circumstances indicate that 62.2 kg N ha^{-1} yr^{-1} (T3) represents the threshold when negative slope of the CO_2 flux to the WFPS was steeper in T4 than other treatments (**Figure 5.8 (a))**. This suggests that 1% decreased of WFPS would increase 3.18 mg C m^{-2} hr^{-1} of CO_2 flux when peat fertilized with high N rates particularly at 124.3 kg N ha^{-1} yr^{-1}. Besides that, positive slope of the N_2O emissions to the CO_2 emission was steeper in T3 and T4 than T1 and T2, reflecting that changes of N_2O emissions with the changes of CO_2 emissions was larger when peat was fertilized with N beyond 62.2 kg N ha^{-1} yr^{-1} (**Figure 5.8** (**b**)). Several studies had shown the positive relationship between CO_2 and N_2O emissions indicated soil organic matter decomposition contributed to N_2O flux (Shimizu et al., 2010; Toma and Hatano, 2007). Kimura et al. (2012) reported that soil organic matter decomposition was closely related to the N_2O production through the provision of C as an energy source to denitrifiers.

5.4.2 Temporal Effects of GWL on WFPS and CO_2 fluxes

It was mainly found that the lowering of the water table level in oil palm plantations exposes peat to oxygen and leads to accelerated peat decomposition and increased the CO_2 flux (Furukawa et al., 2005; Couwenberg et al., 2010; Hooijer et al., 2010; Hirano et al., 2014). However, GWL flux showed negative relationship with CO_2 fluxes only in year 2010 and 2011 ($p<0.05$), which was during young stage of oil palm cultivation (**Figure 5.5**). Significant positive relationship between GWL and WFPS were also obtained only in 2010 and 2011 ($p<0.001$) (**Figure 5.6**). Relationship between GWL and WFPS did not significant as the palm's age increasing ($p>0.05$), possibly due to the disturbance of capillary rise by the increase of plant water uptake as shown by the positive relationship between WFPS and oil palm yield ($p<0.001$) (**Chapter 4**, **Figure 4.4**). Insignificant effect of GWL on CO_2 flux was also reported by Watanabe et al. (2009), Melling et al. (2005) and Parmentier et al. (2009). According to Jauihiainen et al. (2012), peatland with low GWL and controlled permanent drainage, the relationship between GWL and soil moisture is weaker as compared to the peatlands with high GWL and without controlled drainage. Marwanto et al. (2019) also reported that CO_2 flux from the older oil palm plantations is affected more by the timing of cultivation than by the GWL. Annual cumulative CO_2 emissions for oil palm plantation with GWL between -91 to -36 cm from previous studies ranged from 10.3 to 28.4 t C ha^{-1} yr^{-1} (Melling et al., 2005; Dariah et al., 2014; Husnain et al., 2014; Marwanto et al., 2019). Our values were lower than and within the range (7.7±1.2 to 17.1±3.9 t C ha^{-1} yr^{-1}).

Negative significant relationship between WFPS and CO_2 fluxes in all years except for 2012 (**Figure 5.7**) indicate that WFPS was the dominant factor of CO_2 fluxes instead of GWL. As shown in **Figure 5.1**, CO_2 fluxes were decreased with time which concurred with the increasing in WFPS and decreasing of soil porosity (**Figure 5.2 (b) and (d))**. These relationships were supported by negative relationship between WFPS and porosity ($p<0.001$) (**Figure 5.4(a)**) and positive relationship between CO_2 fluxes and porosity ($p<0.001$) (**Figure 5.4(b)**). Soil porosity was affected by bulk density as shown in **Figure 5.4(c).** Constant peat decomposition after drainage and compaction would decrease soil porosity and increase WFPS over time. Decreasing in soil porosity would increase micropore volume, capillary water and water retention capacity which led to increase in WFPS with time. This allows anaerobic conditions to prevail and depress aerobic microbial activity, decreasing CO_2 emissions over time. Importance of bulk density on capillary rise was shown by Nugraha et al. (2016) which shown that the highest value of water content in peat was achieved in the treatment of bulk density of 0.2 g cm^{-3} than bulk density of 0.1 g cm^{-3}. In year 2012, there was no significant relationship between WFPS and CO_2 fluxes ($p>0.05$) which possibly due to sudden increased of CO_2 fluxes between October 2012 to January 2013 following an increase in GWL and WFPS during wet season, demonstrating that groundwater influx and higher WFPS may enhance C degassing and push the gas into the atmosphere (**Figure 5.1, Figure 5.2 (a) and (b)**). Annual cumulative CO_2 emissions were decreased with time also agreeable by a few studies (Kusin et al., 2015; Cooper et al., (2020) but contrast with findings by Melling et al. (2011) and Hergoualc'h et al. (2017) which reported that CO_2 emission increased with age of palms due to increase in root biomass. Temporal increased in WFPS not only decreased both CO_2 and N_2O emissions but coincided with increased oil palm yield as shown by the positive relationship between WFPS and oil palm yield (**Chapter 4**, **Figure 4.4**).

5.5 Conclusions

Application of N fertilizers had no significant effects on CO_2 emissions which related to high and increased C/N ratio (>20) with time, suggesting that quality of organic matter play significant roles in peat decomposition with time. Despite no significant effects of N fertilization on CO_2 emissions, N fertilizers application particularly beyond 62.2 kg N ha^{-1} yr^{-1} resulted in larger effects of WFPS on CO_2 fluxes and CO_2 emissions on N_2O emissions. Thus, the condition of soil substrate plays an important role on degrees of N fertilization effects on CO_2 emissions from cultivated tropical peatland. Significant relationship between GWL and WFPS and CO_2 fluxes were found only during early stage of oil palm showed that water uptake by oil palm would play significant roles in affecting the relationship between GWL, WFPS and CO_2 fluxes. Positive relationship between oil palm yield and WFPS ($p<0.001$) and negative relationship between WFPS and CO_2 fluxes suggest that higher

WFPS is better to increase oil palm yield and decrease CO_2 emissions as the palms getting mature. More understanding on water management in different phase of oil palm would be essential for reducing CO_2 emissions and increasing oil palm yield from tropical peatlands.

CHAPTER 6

Incubation Study: Effect of Different N Rates on Peat Decomposition Under Different Soil Moisture Level

6.1 Introduction

Conversion of tropical peat land into oil palm plantations which requires drainage and N fertilization has created great concern on its impact on greenhouse gases (GHGs). Drainage and nitrogen (N) fertilization as one of the important management practices for oil palm plantation were reported would accelerate peat decomposition and mineralization rates, leading to increase in carbon dioxide (CO_2) and nitrous oxide (N_2O) release into the atmosphere (Hadi et al., 2000; Jauhiainen et al., 2011; Hergoualc'h and Verchot, 2014; Comeau et al., 2016). It was reported that N_2O emission increased with the increase of CO_2 emission by peat decomposition (Mu et al., 2014; Kimura et al., 2012).

As shown in Chapter 4, results from long-term field measurement of an effect of N fertilization on annual cumulative N_2O emissions which was collected from fertilization band had significantly increased the annual cumulative N_2O emissions only for T4 in 2010 ($p<0.05$), 2011 ($p<0.05$), 2012 ($p<0.01$), and 2016 ($p<0.05$). However, N fertilizer had no significant effect on annual cumulative CO_2 emissions in each year ($p=0.448$) as shown in Chapter 5, corresponding to other studies (Watanabe et al., 2009; Sakata et al., 2014). Our field experiment measured soil respiration which composed of root and heterotrophic respiration, thus effects of N fertilization on peat decomposition was difficult to determine without isolating the root respiration from soil respiration.

The WFPS has been reported to be dominant factor for both CO_2 (Melling et al. 2005) and N_2O emissions in tropical peatland (Chaddy et al., 2019). Previous studies showed that soil N_2O emissions increased when WFPS increased from 50% to 70% and decreased when

WFPS went above 70% (Davidson et al., 2000; Ishikura et al., 2018; Chaddy et al., 2019). Soil properties such as soil pH (Ishikura et al., 2018), C/N ratio (Swails et al., 2017), water extractable organic carbon (WEOC) and microbial biomass carbon (MBC) (Ghani et al., 2003) were related to soil organic matter decomposition. With the application of N fertilizers, the aforementioned factors would be affected, which then affect peat decomposition. Application method of fertilizers in oil palm plantations should also be considered as differentiating the fertilized area from the non-fertilized area between the palms is important for spatial stratification to appropriately scale-up the emissions estimates. Thus, incubation study was conducted to investigate the effect of N fertilizer on peat decomposition under different water-filled pore space (WFPS).

6.2 Materials and Methods

As described in Chapter 3 (Section 3.2), the laboratory incubation study was conducted to examine the effects of N fertilization on CO_2 and N_2O emissions at two different peat moistures for comparison with field study results. Soil was incubated with four fertilization treatments at two different soil moisture (50% and 80% WFPS) were arranged by a randomized complete design. The treatments were; T1 (control- 0 mg N kg^{-1} soil), T2 (780 mg N kg^{-1} soil), T3 (1550 mg N kg^{-1} soil) and T4 (3110 mg N kg^{-1} soil) under 50% WFPS and 80% WFPS. These N rates were ten times higher rates compared to the rates estimated from average of the N application rate in the field treatment which are 78 mg kg^{-1} soil for T2, 155 mg kg^{-1} soil for T3, and 311 mg kg^{-1} soil for T4 as rate in incubation study was based on area which was affected by fertilization application. In field experiment, width of circumference fertilizer area was approximately 0.15 m with an area 1.9 m^2. However, fertilizer-induced area would be larger due to fertilization leakage from fertilization area to the outside the fertilization area which can caused higher N_2O emissions outside fertilization area than inside fertilization area (Oktarita et al., 2017). Therefore, to determine the area which was affected by fertilization application, soil CO_2 and N_2O flux were measured at 2 m (fertilizer circumference – IF) and 2.5 m (outside fertilizer circumference – OF) (**Figure 6.1**). Distance at 2.5 m distances from the palm trunk were representative of the rooting zone at the plantation scale (Dariah et al., 2014). The measurements were done in field experimental site of T3 (420g N palm^{-1}) (Recommended rate) in July, October and December 2018. Measurements were done 5 days after fertilization for 5 consecutive days.

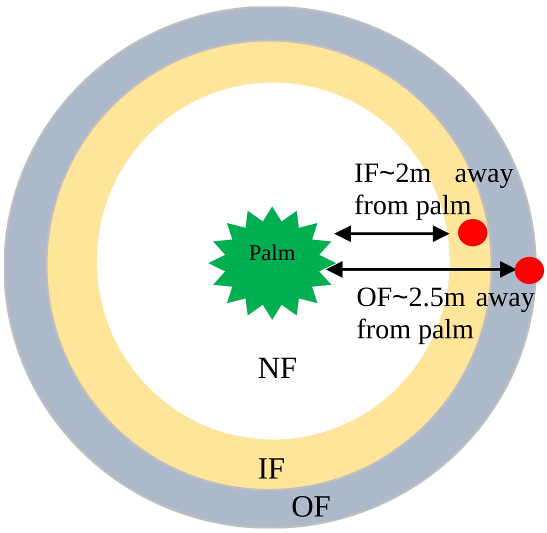

Figure 6.1 Layout of experimental design for CO_2 and N_2O fluxes measurement at 2m and 2.5m distance from palm. NF, IF and OF are area of non-fertilized area, inside fertilizer circumference (width ~15 cm) and outside fertilizer circumference.

As shown in **Figure 6.2 (a)**, there were no significant differences between CO_2 fluxes in IF and OF ($p=0.489$) but N_2O fluxes in OF was significantly higher than IF ($p<0.001$), indicating that N fertilizers most likely leached from IF to OF (**Figure 6.2 (b)**). This was agreed with findings by Oktarita et al. (2017). It was observed that the presence of higher slope near oil palm trunk would probably cause fertilizers easily leached to lower slope. The width of circumference fertilizer area was approximately 0.15 m but it was shown that fertilizers affected area would likely to be larger than fertilized area particularly on N_2O emissions (**Figure 6.1**). Thus, the calculation of amount of N fertilizers for incubation study was based on area which was affected by fertilization application.

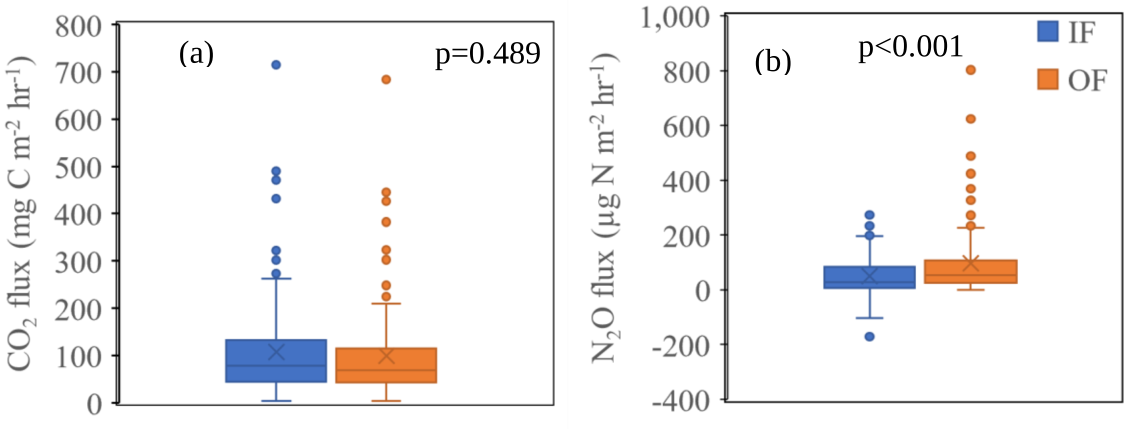

Figure 6.2 Boxplot showing the distribution of (a) CO_2 and (b) N_2O fluxes at 2 m (IF) and 2.5 m distance (OF) from palm (n=312-327). Significant difference between treatment using t-test at $p < 0.05$.

From this, N fertilizer amount for incubation study was calculated based on fertilizers affected area as follow:

$$(\mathrm{NF} + \mathrm{IF} + \mathrm{OF})\ or\ NF = \pi r^2$$

$$A = (NF + IF + OF) - NF$$

$$AS = \frac{N}{A \times D \times Bd}$$

where r is the radius of circle (r (NF+IF+OF)=2.5 m, r (NF) =2 m); A is the area of fertilized affected area (m^2); NF, IF an OF (m^2) area of non-fertilized area, inside fertilizer circumference and outside fertilizer circumference, respectively (**Figure 6.1)**; AS is the amount of N fertilizer needed for incubation study (mg kg^{-1}dry soil); N is the amount of N fertilizer per palm (T2=210g N palm^{-1}; T3=420g N palm^{-1}; T4=840g N palm^{-1}); D (m) is soil depth taken for incubation study (0.25 m) and Bd is the average bulk density from 0-25 cm peat depth (0.16 tan m^{-3}). Incubation was conducted by placing all the jars in an incubator at

28 °C for 12 weeks. Concentration of CO_2, N_2O, water extractable organic carbon (WEOC) were measured in weekly basis at initial stage, 1,2,3,4,5,6,7,8,9,10,11 and 12 weeks. Gross N mineralization (GM), net N mineralization (NM) and net nitrification (NN) were also calculated. Two-way ANOVA was used to evaluate the effect of different N treatments and soil moisture on CO_2, N_2O and soil properties. Pearson's correlation test and stepwise regression were conducted to identify the main factors influencing CO_2 and N_2O emissions.

6.3 Results

6.3.1 Fluxes of CO_2 and N_2O

As shown in **Figure 6.3(a) and (b)**, application of N fertilizers had no significant effects on CO_2 fluxes in both WFPS in each week ($p>0.05$). Under 50% and 80% WFPS, CO_2 fluxes in all treatments steeply dropped on week 4 and then increased on week 5. Although there were no significant differences, it was observed that CO_2 fluxes in fertilized treatments were higher than control from week 1 to 3 under 80% WFPS while higher CO_2 fluxes in control than fertilized were observed from week 5 to 12 under 50% WFPS. Higher WFPS (80%) resulted in higher CO_2 fluxes than 50% WFPS.

In **Figure 6.3(c) and (d)**, N_2O fluxes had no significant differences among treatments under 50% and 80% WFPS in each week ($p>0.05$) except for N_2O fluxes on week 7 under 80% WFPS ($p<0.001$). In 50% WFPS, after decreased on week 4, N_2O fluxes from control were found to increase in larger magnitude from week 5 to 7 compared to fertilized treatments before it started to decrease from week 8 to 9. All treatments were steeply decreased on week 9 which then increased again on week 10 (**Figure 6.3(c)**). In contrast to 50% WFPS, instead of decreased on week 2, N_2O fluxes under 80% WFPS were increased and decreased on week 3. The trend then constantly low onwards until week 6. On week 7, N_2O flux in T3 and T4 were significantly higher than control ($p<0.001$), contributing about twice higher than N_2O flux in control. The fluxes were then dropped on week 8 (**Figure 6.3(d)**).

As shown in **Table 6.1**, there was no significant effect of N fertilization on cumulative CO_2 and N_2O emissions under 50% WFPS (CO_2; p=0.3670, N_2O; p=0.1689) and 80% WFPS (CO_2; p=0.8865, N_2O; p=0.9032). However, it was found that only N_2O emissions from fertilized treatments were significantly affected by soil moisture where cumulative N_2O emissions in 80% WFPS were significantly higher than 50% WFPS in but only occurred in T2 (p<0.05), T3 (p<0.01) and T4 (p<0.01).

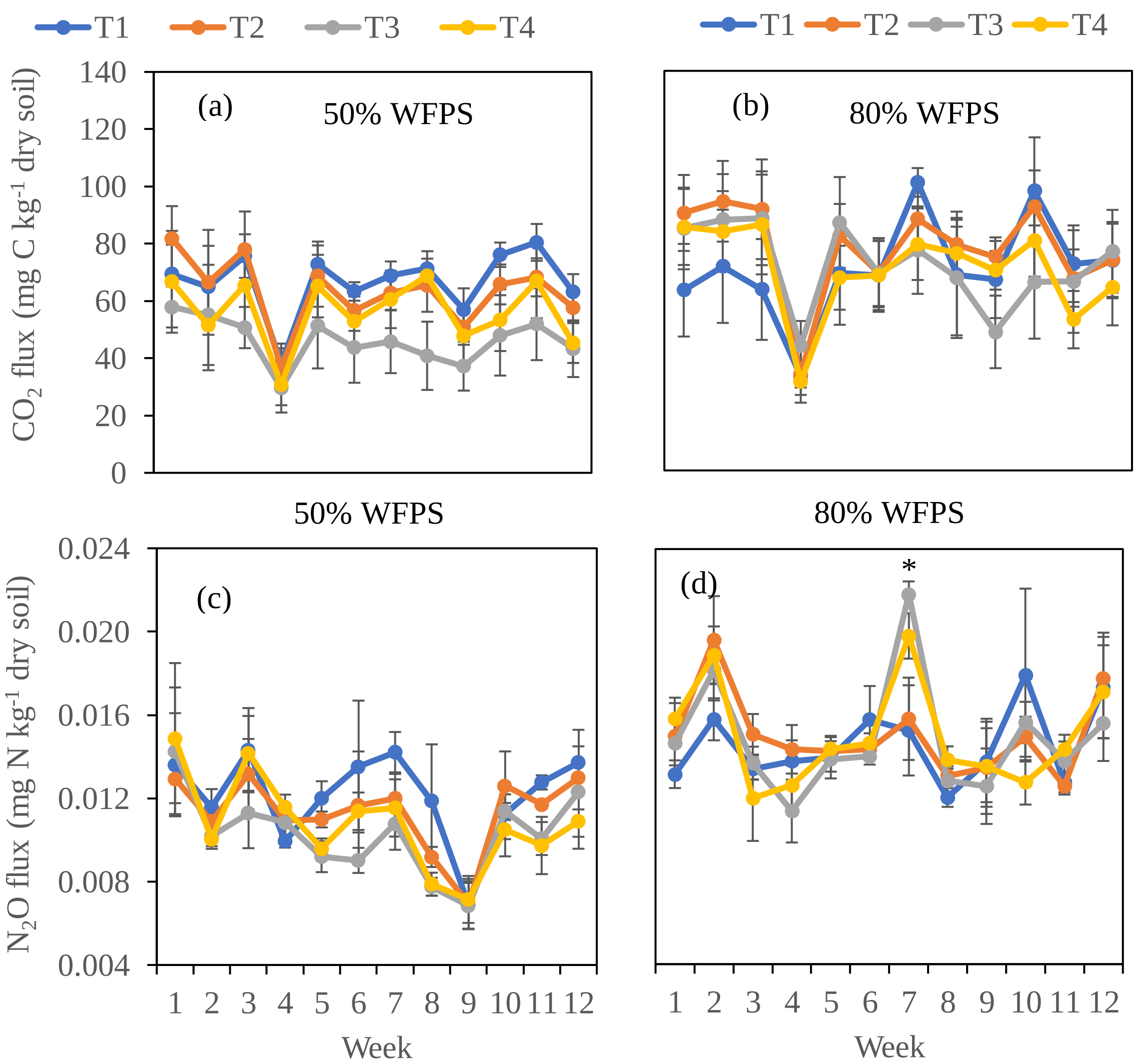

Figure 6.3 (a-b) Carbon dioxide and (c-d) N_2O fluxes over 12 weeks in each treatment at 50% and 80% WFPS. Error vars represent standard deviation of means (n=5). * indicates significance significant difference at $p < 0.05$.

Table 6.1 Cumulative GHGs emissions on 12 weeks of sampling (n=5) (mean±std).

N rates	CO_2 (mg C kg^{-1} $12w^{-1}$)		N_2O (mg N kg^{-1} $12w^{-1}$)	
	50% WFPS	80% WFPS	50% WFPS	80% WFPS
T1	5072.9±650	5376.1±2145	0.92±0.1	0.98±0.1
T2	4799.3±1187	5953.8±1128	0.86±0.1^{b}	1.01±0.1^{a}
T3	3545.9±1824	5480.8±2031	0.78±0.1^{b}	1.00±0.1^{a}
T4	4248.2±1701	5074.2±1601	0.82±0.1^{b}	1.03±0.1^{a}

ANOVA CO_2

Source	df	Mean Square	F Value	p-value
N rate	3	1770855.44	0.69	0.5665
WFPS	1	11123442.58	4.32	0.0458
N rate*WFPS	3	1168259.41	0.45	0.7167
Error	32	2576849		

ANOVA N_2O

Source	df	Mean Square	F Value	p-value
N rate	3	0.0067446	0.64	0.5979
WFPS	1	0.26069257	24.55	<0.0001
N rate*WFPS	3	0.01380839	1.3	0.2913
Error	32	0.01062077		

The letters (a, b) in the row indicate a significant difference between treatments using Tukey's Test at $p < 0.05$.

6.3.2 Soil Properties

As shown in **Table 6.2**, N fertilization was significantly decreased both soil pH and C/N ratio and significantly increased NH_4^+ concentrations under both WFPS (p<0.001). However, there were no significant differences in NO_3^-, WEOC and MBC among treatments under both 50% WFPS (NO_3^-, p=0.9115; WEOC, p=0.9861; MBC, p=0.5087) and 80% WFPS (NO_3^-, p=0.4947; WEOC, p=0.4398; MBC, p=0.6184). As shown in **Figure 6.4 (a) and (b)**, soil pH in fertilized treatments (range from 3.3 to 3.9) were lower than control (range from 4 to 4.7) under both WFPS. Soil NH_4^+ from fertilized treatments were higher than control in both 50% and 80% **(Figure 6.4 (c) and (d))**. Generally, there were no clear differences among treatments on NO_3^- in each WFPS. Range of soil NO_3^- under 50% WFPS was from

52 to 76.7 mg N kg^{-1} while range of soil NO_3^- under 80% WFPS was 75 to 113 mg N kg^{-1} which indicate that higher soil moisture increased NO_3^- than 50% WFPS (**Figure 6.4 (e) and (f)**). In **Figure 6.4 (e)**, soil NO_3^- in all treatments under 50% WFPS were constant except for T4 on week 6 which steeply dropped, coinciding to the drop of NH_4^+ in **(Figure 6.4 (d)**. Similar to NH_4^+ under 80% WFPS, peak of NO_3^- was found in T3 and T4 on week 5 **(Figure 6.4 (f)**. The initial C/N ratio for T1, T2, T3 and T4 under 50% WFPS were 30.9, 29.0, 27.4 and 25.5, respectively while initial C/N ratio for T1, T2, T3 and T4 under 80% WFPS were 30.4, 28.5, 27.0 and 24.1, respectively. Under 50% WFPS, higher C/N ratio for T1 was observed on week 1 which after that decreased to stable trend while fertilized treatments were generally stable (**Figure 6.4 (g)**). The C/N ratio for all treatments under 80% WFPS were also rather stable throughout the study period (**Figure 6.4 (h)**). The WEOC in all treatments under 50% WFPS were increased from week 0 until it peaked on week 6 except for control (**Figure 6.4 (i)**). WEOC of T4 remained higher until week 7 for T4 and decreased and remained constant from week 8. Peak of control only found later which was on week 8. Under 80% WFPS, steep peak of WEOC for T1, T2 and T3 appeared on week 4 and remained high until week 5 for T3 (**Figure 6.4 (j)**). Under 50% WFPS, MBC in fertilized treatments decreased from week 0 to week 4 and even until week 5 in T3. MBC started to increase on week 5 in T2 and T4 (**Figure 6.4 (k)**). Steep peak of MBC for T1, T2 and T3 appeared on week 5 and decreased on week 7. MBC in all treatments after week 7 increased towards the end of incubation (**Figure 6.4 (l)**).

Table 6.2 Soil properties in each treatment under different WFPS (n=13).

50% WFPS				
Variables	T1	T2	T3	T4
Soil pH	4.11 (0.12)^{a}	3.58 (0.06)^{b}	3.47 (0.05)^{c}	3.37 (0.04)^{d}
NH_4^+ (mg N kg^{-1})	494.1 (408)^{d}	1377.3(127)^{c}	2473.4(207)^{b}	4282.5(349)^{a}
NO_3^- (mg N kg^{-1})	66.6 (3.1)	67.2 (3.3)b	66.2 (3.4)	67.1 (5.7)
C/N ratio	30.9 (1.7)^{d}	29.0 (0.6)^{c}	27.4 (0.4)^{b}	24.8 (0.4)^{a}
WEOC (mg kg^{-1})	1587.5 (1127)	1741.7 (1717)	1768.6 (1395)	1772.4 (1502)
MBC (mg kg^{-1})	876.7 (400)	821.6 (254)	672.8 (421)	851.5 (388)
80% WFPS				
Variables	T1	T2	T3	T4
Soil pH	4.42 (0.17)^{a}	3.80 (0.36)^{ab}	3.51 (0.08)^{b}	3.40 (0.05)^{c}
NH_4^+ (mg N kg^{-1})	428.7 (170)^{d}	1299.8 (232)^{c}	2458.9 (402)^{b}	4308.1 (531)^{a}
NO_3^- (mg N kg^{-1})	84.0 (2.5)	83.4 (2.0)	85.8 (8.9)	82.2 (7.5)
C/N ratio	29.4 (1.0)^{d}	27.9 (0.4)^{c}	26.4 (0.4)^{b}	24.0 (0.5)^{a}
WEOC (mg kg^{-1})	2618.2 (2690)	1537.9 (1039)	1982.1 (1244)	1862.1 (1326)
MBC (mg kg^{-1})	1046.3 (503.1)	1080.8 (386.4)	961.9 (513.2)	852.4 (481.4)

The letters (a, b, c, d) in the row indicate a significant difference between treatments using Tukey's Test at $p < 0.05$.

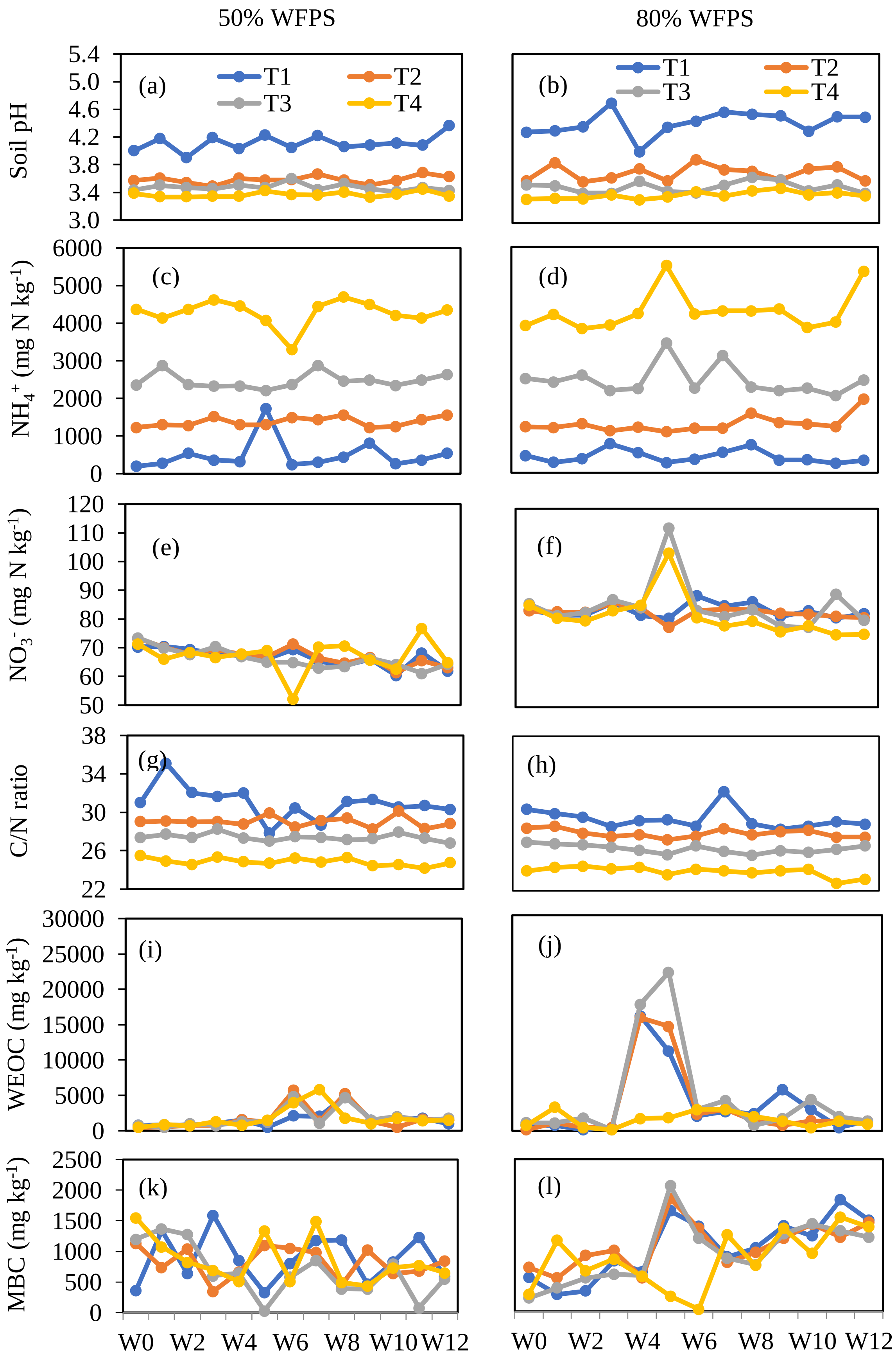

Figure 6.4 (a-b) Soil pH, (c-d) NH_4^+-N, (e-f) NO_3^--N, (g-h) C/N ratio, (i-j) WEOC and (k-l) MBC of each nitrogen treatments at 50% and 80% WFPS.

6.3.3 Factors Influencing CO_2 and N_2O Fluxes

Pearson's correlation matrix of CO_2, N_2O fluxes and soil properties at 50% and 80% WFPS are shown in **Table 6.3**. Under 50% WFPS, CO_2 fluxes was positively correlated with N_2O fluxes, soil pH ($p<0.01$), C/N ratio and MBC ($p<0.05$) but negatively correlated with NH_4^+-N ($p<0.05$). Positive correlation was obtained between N_2O fluxes and soil pH($p<0.05$) and MBC ($p<0.01$). Under 80% WFPS, CO_2 fluxes was positively correlated with N_2O fluxes but negatively correlated with WEOC only ($p<0.01$). As shown in **Table 6.4**, the strongest predictor for CO_2 flux in both 50% and 80% WFPS were N_2O flux. As shown in **Figure 6.5**, CO_2 fluxes was positively correlated with N_2O fluxes under 50% and 80% WFPS, accounting for 21% and 14% of the variation, respectively. In comparison to field experiment, slope of N_2O emissions to the CO_2 emissions in field experiment was larger than incubation (**Figure 5.8(b)**).

Table 6.3 Pearson's correlation matrix of CO_2, N_2O fluxes and soil properties at 50% and 80% WFPS (n=48).

			50% WFPS				
	N_2O	pH	NO_3^--N	NH_4^+-N	WEOC	C/N	MBC
CO_2	0.457**	0.416**	0.184	-0.339*	-0.078	0.353*	0.367*
N_2O		0.336*	0.074	-0.255	-0.182	0.283	0.429**
pH			-0.046	-0.801**	-0.032	0.786**	0.12
NO_3^--N				0.053	-0.239	0.026	0.360**
NH_4^+-N					0.018	-0.928**	-0.063
WEOC						-0.069	0.011
C/N							0.132
			80% WFPS				
	N_2O	pH	NO_3^--N	NH_4^+-N	WEOC	C/N	MBC
CO_2	0.402**	-0.034	0.113	-0.074	-0.435**	0.128	0.154
N_2O		-0.162	-0.154	0.092	0.037	-0.019	0.024
pH			0.006	-0.772**	0.073	0.763**	0.153
NO_3^--N				0.029	0.02	0.067	-0.055
NH_4^+-N					-0.065	-0.939**	-0.156
WEOC						0.069	0.079
C/N							0.035

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 6.4 Stepwise regression of CO_2 and N_2O fluxes by using pH, NH_4^+-N, C/N ratio, MBC and WEOC at 50% and 80% WFPS (n=48).

	WFPS	Variable	Unstandardized Coefficients	Std. Error	Standardized Coefficients	R^2	p-value
CO_2 flux	50%	Intercept	-15.40	19.83		0.30	0.442
		N_2O	2252.00	821.08	0.37		0.009
		pH	13.18	5.71	0.31		0.026
	80%	Intercept	48.87	9.32			0.000
		N_2O	2410.29	685.40	0.42	0.36	0.001
		WEOC	0.00	0.00	-0.45		0.000
N_2O flux	50%	Intercept	0.01	0.0012		0.29	0.000
		CO_2	0.00006	0.00002	0.35		0.014
		MBC	0.00000	0.000001	0.30		0.030
	80%	Intercept	0.00804	0.00172		0.16	0.000
		CO_2	0.00007	0.00002	0.40		0.005

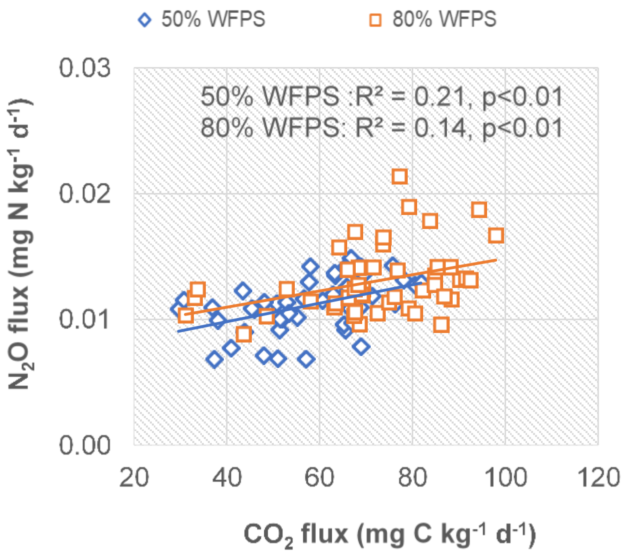

Figure 6.5 Relationship between CO_2 fluxes and N_2O fluxes under different WFPS.

6.3.4 Gross N Mineralization, Net N Mineralization and Net Nitrification

Gross N mineralization (GM), net N mineralization and net nitrification are shown in **Figure 6.6**. It was found that only GM in T3 was significantly lower than other treatments under 50% WFPS ($p<0.01$) while there were no significant differences in GM among fertilization treatments under 80% WFPS (p=0.469) (**Figure 6.6(a)**). Negative NM was found in T4 under 50% WFPS and T1 and T3 under 80% WFPS (**Figure 6.6 (b)**).

In **Table 6.5**, GM was positively correlated with both NO_3-N and MBC ($p<0.01$) while NM had no correlation with any of the soil properties ($p>0.05$). NN was positively correlated with MBC only ($p<0.05$). There was linear positive relationship between MBC and GM ($p<0.01$), accounting about 79% of the relationship **(Figure 6.7).**

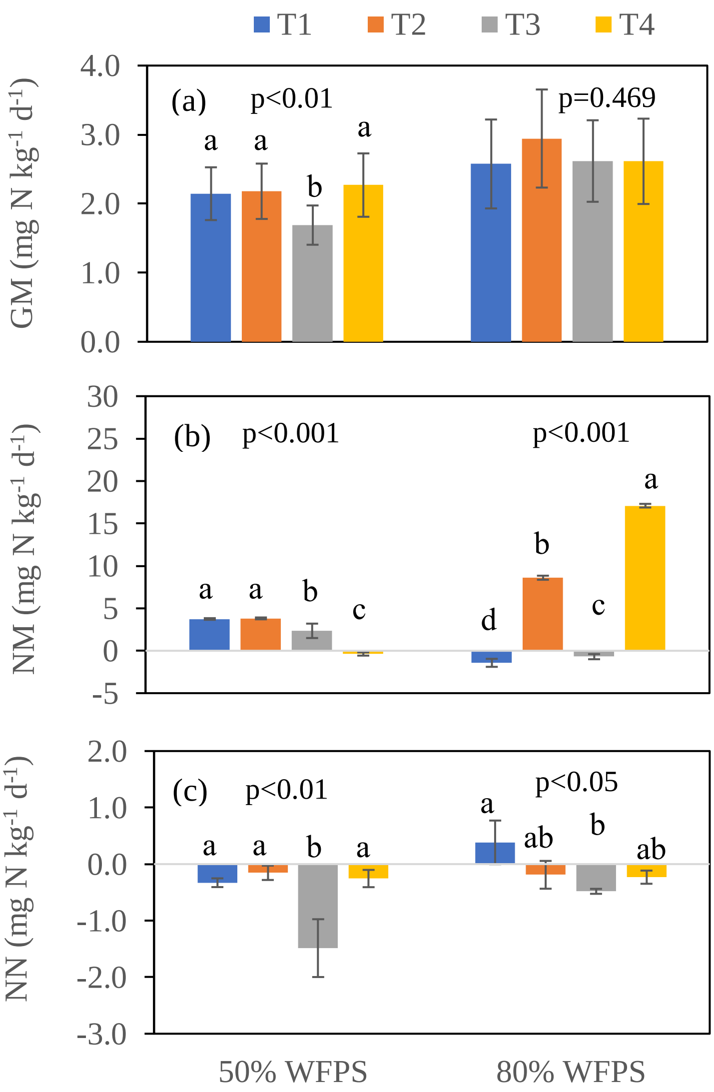

Figure 6.6 (a) Gross N mineralization and (b) net N mineralization and (c) net nitrification in each treatment. The error bars represent the standard deviation.

Table 6.5 Pearson's correlation matrix of GM, NM, NN, and soil properties at 50% and 80% WFPS (n=8).

	GM	NM	NN
GM	-	-	-
NM	0.311	-	-
NN	0.673	0.015	-
pH	0.195	-0.294	0.536
NO_3^--N	0.852**	0.216	0.443
NH_4^+-N	-0.037	0.347	-0.272
WEOC	0.197	-0.165	0.334
C/N	-0.191	-0.377	0.167
MBC	0.891**	-0.046	0.746*

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

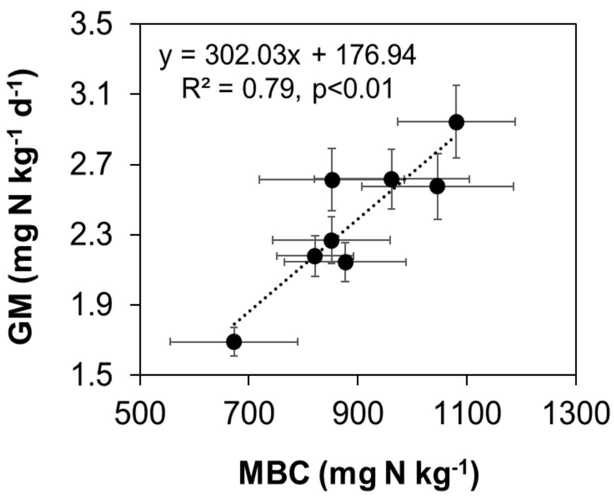

Figure 6.7 Relationship between MBC and GM. Error bars indicate standard error.

6.4 Discussions

6.4.1 Effect of Differences in N Rates and WFPS on CO_2 and N_2O Emissions

In field experiment, only soil respiration, a combination of plant-root, heterotrophic and mycorrhizal respiration (Kuzyakov, 2006) was measured. Thus, incubation study was included in this study to investigate the effect of N fertilization on heterotrophic respiration. As shown in **Table 6.1**, there was no significant effect of N fertilization on cumulative CO_2 emissions in both 50% WFPS ($p=0.3670$) and 80% WFPS ($p=0.8865$). These finding corresponds with results from field studies in Chapter 5, which showed that annual cumulative CO_2 emissions had no significant differences among treatments throughout the study period ($p>0.05$). According to Snyder et al. (2009), soil organic matter with C/N ratios greater than 20 typically requires additional N to support decomposition. Since initial C/N ratio in each N fertilized treatments were between 24.1 to 29.0, N treatment was not sufficient to bring C/N to the level generally required to meet microbial requirements which also explained high C/N ratio in field experiment. However, Swails et al. (2017) reported that although high N treatment (1675 mg N kg^{-1} soil) was sufficient to alleviate N constraints on microbes, but limitation then may have shifted to soil organic matter quality, where soil organic matter becomes increasingly recalcitrant to decomposition.

Incubations study showed that there were no significant effects of N fertilization on cumulative N_2O emissions which was also corresponded to field experiments where annual cumulative N_2O emissions in only T4 was significantly higher than control (Chapter 4). As shown in **Figure 6.3 (d)**, N_2O flux in T3 and T4 on week 7 under 80% WFPS were significantly higher than control ($p<0.001$), coinciding with higher NH_4^+ and NO_3^- on week 5 (**Figure 6.4 (d) and (f)**), suggesting that both nitrification and denitrification may occur simultaneously. Under 80% WFPS, presence of anaerobic microsites within the aerobic soil matrix may likely create the conditions favorable for the occurrence of simultaneous nitrification and denitrification. However, rate of N used was between 780 to 3,110 mg N kg^{-1} soil and based on rate used by Ariffin et al. (2015), (880 mg N kg^{-1} soil), rates in this study would possibly inhibit nitrification rates. As shown in **Figure 6.6(c)**, negative NN indicated that NO_3^--N is immobilized or denitrified. A significant positive relationship was found between NN and MBC ($p < 0.05$) (**Table 6.5**), suggesting that low nitrification rates were due to the limited number of nitrifiers (Han et al., 2012).

As shown in **Table 6.1**, cumulative N_2O emissions were significantly higher in 80% WFPS than 50% WFPS but only occurred in T2 ($p<0.05$), T3 ($p<0.01$) and T4 ($p<0.01$). In contrast, WFPS had no significant effects on cumulative CO_2 emissions ($p>0.05$) (**Table 6.1**). Greatest N_2O emissions occurred at 80% WFPS also reported by other studies which showed that larger N_2O emission potential occurs at WFPS values close to 80% (Inubushi et al. 1996; Dobbie and Smith 2001, 2003) because 80% WFPS condition was not reductive enough to allow the complete reduction to N_2 (Ciarlo et al., 2007). Thus, with application of N fertilizer, magnitude of N_2O emissions would be greater under 80% WFPS. However, effect of WFPS on N_2O emissions in this study were in contrast with field measurements where WFPS more than 70% would decrease N_2O fluxes (**Chapter 4**, **Table 4.7**). In **Chapter 4**, N_2O fluxes increased when WFPS increased from 50% to 70% and decreased afterwards when the WFPS increased to a higher WFPS (>70%) (**Table 4.7**), coinciding with significant negative correlation between WFPS and NO_3^- ($p < 0.05$) when WFPS ranging between 70% and 96% (**Table 4.7**). These could be due to the presence of plant uptake which are not included in incubation study. In the field experiment, oil palm yield was negatively correlated with annual cumulative N_2O emissions, NO_3^- (**Chapter 4, Figure 4.3**) but positively correlated with WFPS ($p<0.001$) (**Chapter 4, Figure 4.4**). These results indicated that higher NO_3^- uptake by oil palm in higher WFPS reduced NO_3^- concentration, resulting in decrease of N_2O emission in higher WFPS. Positive correlation between CO_2 fluxes and

N_2O fluxes were found in both field and laboratory results (**Figure 5.8(b) and Figure 6.5**), suggesting that N_2O emission closely related to peat soil organic matter decomposition. Slope of N_2O emissions to the CO_2 emissions in field experiment was larger than incubation which may due to the presence of plant NO_3^- utilization and likely stimulated root exudation, increasing both CO_2 and N_2O emissions in field. Linear positive relationship was obtained between MBC and GM ($p<0.001$) indicates that greater MBC enhanced gross N mineralization which resulted in higher N_2O production. Higher WFPS and C concentrations from root exudates resulted in greater denitrification rates (Langarica-Fuentes et al., 2018).

6.4.2 Factors Influencing CO_2 and N_2O Fluxes

Pearson's correlation showed that CO_2 fluxes was positively correlated with N_2O fluxes, soil pH ($p<0.01$), C/N ratio and MBC ($p<0.05$) but negatively correlated with NH_4^+-N ($p<0.05$) under 50% WFPS while under 80% WFPS, CO_2 fluxes was positively correlated with N_2O fluxes and negatively correlated with WEOC only ($p<0.01$) (**Table 6.3**). Positive correlation was obtained between N_2O fluxes and both soil pH ($p<0.05$) and MBC ($p<0.01$) under 50% WFPS. As shown in **Figure 6.5**, CO_2 fluxes from both 50% and 80% WFPS were positively correlated with N_2O fluxes ($p<0.01$), which also agrees by findings in field measurements, indicating that soil organic matter decomposition was closely related to the N_2O production through the provision of carbon as an energy source to denitrifiers (Kimura et al.,2012; Mu et al. 2014). Positive correlation between both CO_2 and N_2O fluxes and soil pH suggests that organic matter decomposition, nitrification and denitrification were promoted when soil pH increased (Ishikura et al., 2017; Cuhel et al., 2010; Simek and Copper, 2002). In **Table 6.5**, MBC was positively associated with both GM and NN, demonstrating that MBC is indicative of general soil N cycling in tropical peat.

6.5 Conclusions

Incubations study showed that there was no significant effect of N fertilization on cumulative CO_2 and N_2O emissions under 50% WFPS (CO_2; p=0.3670, N_2O; p=0.1689) and 80% WFPS (CO_2; p=0.8865, N_2O; p=0.9032). These corresponded to field experiments where no significant differences were obtained among treatments in annual cumulative CO_2 emissions and annual cumulative N_2O emissions (Chapter 4 and 5), suggesting that heterotrophic respiration and annual cumulative N_2O emissions had no significant differences among treatments ($p<0.05$). This might be due to microbial decomposition remained limited by C/N ratio and soil organic matter quality where soil organic matter becomes increasingly recalcitrant to decomposition, suggesting that quality of organic matter play significant roles in peat decomposition. Slope of N_2O emissions to the CO_2 emissions in field experiment was larger than incubation suggests that magnitude of peat decomposition on N_2O emissions would be larger in the presence of plant roots which probably due to utilization of NO_3^- by oil palm roots would likely stimulate root exudation which then stimulate microbial activity. Cumulative N_2O emissions in 80% WFPS were significantly higher than 50% WFPS in fertilized treatments ($p<0.001$) which in contrast with field measurements where WFPS more than 70% would decrease N_2O fluxes, suggesting that without N uptake by oil palm, N fertilizers application on tropical peatland would result in larger magnitude of N_2O production in higher soil moisture (80%). This study shows that presence of plant roots is likely affecting the relationship between WFPS and N_2O emissions and relationship between CO_2 emissions and N_2O emissions which need future investigation.

CHAPTER 7

General Discussion

7.1 Achievements of This Study

The expansion of oil palm plantation into tropical peatland has attracted considerable attention especially on the greenhouse gases emissions due to its effect on global warming. Drainage and nitrogen (N) fertilization as pre-requisite were reported to accelerate the rate of peat decomposition and mineralization and enhances soil CO_2 and N_2O emissions to the atmosphere (Page et al., 2011; van Huissteden et al., 2006; Hooijer et al., 2010). A few short-term measurements had been done to investigate the effect of N fertilization on soil CO_2 and N_2O fluxes from oil palm plantation on tropical peatland which mainly used urea as the N source (Sakata et al., 2014; Watanabe et al., Watanabe et al., 2009; Jauhiainen et al., 2012; Comeau et al., 2016). More information and understanding of the key factors influencing the response of soil CO_2 and N_2O emissions due to N fertilization is necessary to develop approaches to mitigate CO_2 and N_2O emissions from cultivated tropical peatland. Long-term studies would be required as different environmental conditions, peat characteristics and depth, agricultural practices (e.g. fertilizer other than urea, E. guineensis variety, etc.) and palm age could display a different response of CO_2 and N_2O emissions to N addition. Finding a suitable nitrogen rate for optimum oil palm growth and yield whilst maintaining low environmental impact is also crucial for the economic growth of the oil palm sector in Malaysia.

Long term field measurement was conducted to quantify soil CO_2 and N_2O emissions by varying the rates of N fertilizers. As shown in Chapter 4, the application of N fertilizer significantly increased the annual cumulative N_2O emissions only for T4 in 2010 ($p = 0.017$), 2011 ($p = 0.012$), 2012 ($p = 0.007$), and 2016 ($p = 0.048$), which were significantly higher than the control. Application of N fertilizer had no significant effect on annual cumulative CO_2 emissions in each year ($p>0.05$) (Chapter 5) possibly due to high C/N ratios and increased with time (20 to 37). Although there were no significance effects of N fertilization on CO_2 emissions, effect of N fertilization on CO_2 emissions should not be ignored as there are many sources of CO_2 fluxes from soil such as microbial respiration of soil organic matter, and plant residue (Kuzyakov, 2006) which are not measured in this study. The response of each components of soil CO_2 fluxes to N fertilization would be different. For instance, in January 2016 and September 2017, only CO_2 flux from T3 was significantly higher than control while in February 2016, CO_2 fluxes from T3 and T4 were significantly lower than control. In July 2016, only CO_2 flux from T4 was significantly lower than control. These indicate that the usage of ammonium sulphate at 62.2 kg N ha^{-1} yr^{-1} as threshold had the potential to increase or reduce CO_2 fluxes. Thus, these findings suggest that to mitigate fertilizer-induced CO_2 and N_2O emissions and at the same time optimize the oil palm yield, N fertilization rate less than 62.2 kg N ha^{-1} yr^{-1} (T3) should be used in oil palm plantation on tropical peatland.

Understanding key factors influencing the response of soil CO_2 and N_2O emissions and the temporal stages in environmental variables and soil properties on CO_2 and N_2O emissions would enable the oil palm plantation to apply suitable management approach to ameliorate issues of GHG emissions. Both GWL and WFPS were significant predictors in all treatments for N_2O fluxes ($p<0.01$) while WFPS was significant predictor in all treatments for CO_2 fluxes was negatively correlated with in all treatments ($p<0.001$) (**Table 4.6**), indicating that hydrology regimes is very important in affecting both CO_2 and N_2O fluxes in oil palm plantation on tropical peatland. As the age of palm increased, both soil CO_2 fluxes and N_2O fluxes were decreased which coincided with the increasing in WFPS and decreasing of soil porosity (**Figure 4.1 and 5.2**). WFPS was strongly affected by soil porosity compared to GWL. Both WFPS and CO_2 fluxes were significantly positively associated with GWL only in 2010 and 2011 (**Table 5.5, Figure 5.5 and 5.6**), suggesting that WFPS was more sensitive to GWL changes in younger phases than older phases which due to the disturbance of capillary rise by the increase of oil palm water uptake as indicated by positive relationship between WFPS and oil palm yield ($p<0.001$) (**Figure 4.4**). Soil N_2O fluxes increased when WFPS increased from 50% to 70% but then decreased when WFPS went above 70% (**Table 4.7**). This phenomenon was observed in the beginning of 2012 where both N_2O flux and NO_3^- decreased in tandem with increased WFPS (> 70%) (**Figures 4.1**). Complete denitrification might have occurred and N_2O was mostly reduced to N_2 when WFPS went above 70% (Davidson et al., 2000; Ishikura et al., 2018). Increasing WFPS likely reduced gas diffusivity in the soil, inhibiting the escape of N_2O and enhancing the probability of its reduction to N_2 (Melling et al., 2007; Smith et al., 1997). Moreover, the low nitrification rate in continuously high WFPS limited the production of NO_3^- for denitrification, leading to low N_2O emissions. Thus, drainage and compaction of the peat prior to oil palm cultivation are important in increasing bulk density and decreased soil porosity, which facilitate higher capillary water and water retention capacity which decreased both CO_2 fluxes and N_2O fluxes with time. The annual oil palm yield in this study was negatively correlated ($p < 0.05$) with annual cumulative N_2O emissions and NO_3^-, suggesting that increased oil palm yield reduced NO_3^- in soil via N uptake, resulting in lower N_2O emissions (**Figure 4.3**). Increased of WFPS with time (>70%) reduced both N_2O and CO_2 emissions and increased oil palm yield, suggesting that bulk density and soil porosity are important for mitigation strategies in cultivated tropical peatland.

As discussed in Chapter 6, an incubation study was conducted to investigate the effect of N fertilization on peat decomposition as the field experiment measured soil CO_2 emissions which composed of root respiration and heterotrophic respiration. Heterotrophic respiration contributes to peat carbon loss to the atmosphere (Bond-Lamberty and Thompson 2010; Hergoualc'h and Verchot 2011). However, to separate root respiration from total soil respiration is difficult. Here we opted for the incubation of root-free soil. N fertilization had no significant effect on CO_2 emissions and N_2O emissions as in field experiment. High C/N ratio (>20) after N fertilizers application explained the insignificant effect of N fertilization on cumulative CO_2 and N_2O emissions in both field experiment and incubation study under 50% WFPS ($p>0.05$), suggesting that quality of organic matter play significant roles in peat decomposition. However, it was found that N fertilization may likely contribute to larger magnitude of N_2O emissions in higher soil moisture (80% WFPS) (**Table 6.1**), suggesting that N fertilization may likely contribute to larger magnitude of N_2O emissions in higher soil moisture which in contrast with field measurements where WFPS more than 70% would decrease N_2O fluxes (**Table 4.7).** In Chapter 4, N_2O fluxes increased when WFPS increased from 50% to 70% and decreased afterwards when the WFPS increased to a higher WFPS (>70%) (**Table 4.7**), coinciding with significant negative correlation between WFPS and NO_3^- ($p < 0.05$) when WFPS ranging between 70% and 96% (**Table 4.7**). These could be due to the presence of plant uptake which are not included in incubation study. In the field experiment, oil palm yield was negatively correlated with annual cumulative N_2O emissions and NO_3^- (**Figure 4.3**) but positively correlated with WFPS ($p<0.001$) (**Figure 4.4**). These results indicated that higher NO_3^- uptake by oil palm in higher WFPS reduced NO_3^- concentration, resulting in decrease of N_2O emission in higher WFPS. Slope of N_2O emissions to the CO_2 emissions in field experiment was larger than incubation (**Figure 5.8(b) and Figure 6.5**) which may due to the presence of plant NO_3^- utilization and likely stimulated root exudation, increasing both CO_2 and N_2O emissions in field. As shown in **Figure 6.6(c)**, negative net nitrification (NN) indicated that NO_3^--N is immobilized or denitrified. A significant positive correlation was found between NN and MBC ($p < 0.05$)

(**Table 6.5)**, suggesting that low nitrification rates were due to the limited number of nitrifiers (Han et al., 2012).

7.2 Shortages and Perspective

In the field experiment, oil palm yield was negatively correlated with annual cumulative N_2O emissions and NO_3^- (**Figure 4.3**) but positively correlated with WFPS ($p<0.001$) (**Figure 4.4**), which suggesting that higher NO_3^- uptake by oil palm in higher WFPS reduced NO_3^- concentration, resulting in decrease of N_2O emission in higher WFPS. Without N uptake by oil palm, N fertilizers application on tropical peatland would result in larger magnitude of N_2O production in higher soil moisture (80%) and magnitude of peat decomposition on N_2O emissions would be larger in the presence of plant roots which probably due to utilization of NO_3^- by oil palm roots would likely stimulate root exudation which then stimulate microbial activity. However, this study was limited to the effect of N and water uptake by oil palms on CO_2 and N_2O flux, at least until the completion of the planting cycle. Due to incubation root-free soil used, the relevance of the findings about the controlling factors of heterotrophic respiration in the field remains to be confirmed in the future.

7.3 Conclusions

Mitigate fertilizer-induced CO_2 and N_2O emissions and at the same time optimize the oil palm yield, N fertilization rate less than 62.2 kg N ha^{-1} yr^{-1} (T3) would be suitable in oil palm plantation on tropical peatland. Thus, drainage and compaction of the peat prior to oil palm cultivation are important in increasing bulk density and decreased soil porosity, which facilitate higher capillary water and water retention capacity which decreased both CO_2 fluxes and N_2O fluxes with time. This study also suggests that higher WFPS is better to increase yield and decrease N_2O emission as the palms getting mature.

CHAPTER 8

Summary

Introduction

Tropical peat swamp forests are largely composed of coarse woody material from fallen trees, branches, and dead roots which develop under conditions of near continuous soil saturation that leads to anaerobic conditions which dramatically slows decomposition. Thus, tropical peat swamp forests are seen to be an important role in the global carbon (C) cycle and has contribution to climate change. The conversion of tropical peat swamp forest into oil palm plantation requires drainage and fertilization which typically accelerates the rate of peat mineralization and enhances soil CO_2 and N_2O emissions to the atmosphere. While effects of nitrogen (N) fertilizers from cultivated tropical peatland are still limited, the understanding of this subject is essential to develop the mitigation approach for sustainable management of tropical peatland for agriculture. Long term studies are essential as environmental conditions and peat characteristics with time could display a different response of the greenhouse gases to N addition. Besides, finding a suitable N rate for optimum oil palm growth and yield whilst maintaining low environmental impact is also crucial for the economic growth of the oil palm sector in Malaysia. Long-term field measurement was conducted (i) to quantify soil N_2O emissions by varying the rates of N fertilizers and the key factors influencing the response of soil N_2O emissions under N fertilization were identified (ii) to quantify the annual soil CO_2 emissions from an oil palm plantation on a tropical peat soil from different N rates, to identify the regulatory factors affecting soil CO_2 fluxes over time and to understand the temporal effect of groundwater level (GWL) on CO_2 fluxes. On the other hand, incubation study was conducted to (iii) investigate the effect of N fertilizer on peat decomposition under different water-filled pore space (WFPS).

Materials and methods

Field experiment: A field experiment was conducted to quantify the CO_2 and N_2O emissions from soil in an oil palm plantation (*Elaeis guineensis* Jacq.) located in a tropical peatland in Sarawak, Malaysia. The study was conducted from January 2010 to December 2013 and resumed from January 2016 to December 2017. Gas measurements were done in the first week of every month on a non-rainy day, 1 week after fertilization, using a closed chamber method. The experiment used a randomized complete block design with four different N rates; control (T1, without N fertilization), low N (T2, 31.1 kg N ha^{-1} yr^{-1}), moderate N (T3, 62.2 kg N ha^{-1} yr^{-1}), and high N (T4, 124.3 kg N ha^{-1} yr^{-1}) in three blocks (three replications). Air temperature, relative humidity, soil temperature at 5 cm and 10 cm, GWL, and rainfall were also measured. Soil properties such as bulk density, soil porosity, WFPS, soil pH, nitrate (NO_3^-), sulphate (SO_4^{2-}), ammonium (NH_4^+), loss on ignition (LOI), total C and total N were also measured. Oil palm yield, parameterized as the fresh fruit bunch (FFB) in each palm of each treatment block, were harvested, weighed, and recorded.

Incubation study: Peat soil was incubated with four fertilization treatments at two different soil moisture (50% and 80% WFPS) were arranged by a randomized complete design. The treatments are; T1 (control- 0 mg N kg^{-1} soil), T2 (780 mg N kg^{-1} soil), T3 (1,550 mg N kg^{-1} soil) and T4 (3,110 mg N kg^{-1} soil) under 50% WFPS and 80% WFPS. Concentration of CO_2, N_2O, soil pH, water extractable organic carbon (WEOC), nitrite (NO_2^-), NO_3^-, NH_4^+, SO_4^{2-}, total C, total N and microbial biomass carbon (MBC) were measured in weekly basis at initial stage, 1,2,3,4,5,6,7,8,9,10,11 and 12 weeks. Gross N mineralization (GM), net N mineralization and nitrification were also calculated.

Soil N_2O emissions under different N rates in an oil palm plantation on tropical peatland.

Application of the N fertilizer significantly increased annual cumulative N_2O emissions for T4 only in the years 2010 (p = 0.017), 2011 (p = 0.012), 2012 (p = 0.007), and 2016 (p = 0.048). The highest average annual cumulative N_2O emissions were recorded for T4 (41.5 ± 28.7 kg N ha^{-1} yr^{-1}), followed by T3 (35.1 ± 25.7 kg N ha^{-1} yr^{-1}), T1 (25.2 ± 17.8 kg N ha^{-1} yr^{-1}), and T2 (25.1 ± 15.4 kg N ha^{-1} yr^{-1}), indicating that the N rates of 62.2 kg N ha^{-1} yr^{-1} and 124.3 kg N ha^{-1} yr^{-1} increased the average annual cumulative N_2O emissions by 39% and 65%, respectively, as compared to the control. The N fertilization had no significant effect on annual oil palm yield (p = 0.994). Alternating between low (deeper than −60 cm) and high GWL (shallower than −60 cm) enhanced nitrification during low GWL, further supplying NO_3^- for denitrification in the high GWL, and contributing to higher N_2O emissions in high GWL. The emissions of N_2O ranged from 17 µg N m^{-2} hr^{-1} to 2447 µg N m^{-2} hr^{-1} and decreased when the WFPS was between 70% and 96%, suggesting the occurrence of complete denitrification. A positive correlation between N_2O emissions and NO_3^- at 70%–96% WFPS indicated that denitrification increased with increased NO_3^- availability. Oil palm yield was negatively correlated with annual cumulative N_2O emissions, and NO_3^- ($p<0.05$). At the same time positive correlation was found between WFPS and oil palm yield ($p<0.001$). These suggest that higher NO_3^- uptake by oil palm in higher WFPS and reduced NO_3^- concentration, resulting in decrease of N_2O emission in higher WFPS. Based on their standardized regression coefficients, the effect of GWL on N_2O emissions increased with increased N rate ($p < 0.001$). Both nitrification and denitrification increased with increased N availability, making both processes important sources of N_2O in oil palm cultivation on tropical peatland.

Effect of ground water level control and N fertilization on CO_2 fluxes from oil palm plantation on tropical peatland.

Application of N fertilizer had no significant effect on annual cumulative CO_2 emissions in each year (p=0.448), ranging from 7.7 to 16.6 t C ha^{-1} yr^{-1} for T1, 9.8 to 14.8 t C ha^{-1} yr^{-1}1 for T2, 10.5 to 16.8 t C ha^{-1} yr^{-1} for T3 and 10.4 to 17.1 t C ha^{-1} yr^{-1} for T4 which possibly due to high C/N ratios and increased with time (20 to 37). Soil CO_2 fluxes were positively correlated with N_2O fluxes, rainfall, soil porosity, air temperature, soil temperature, soil pH, and NO_3^--N while negative correlations were obtained between CO_2 fluxes and oil palm yield, WFPS, GWL, relative humidity and C/N ratio. By using the overall data, CO_2 flux showed significantly positive correlation with both WFPS ($p<0.001$) and N_2O fluxes ($p<0.05$) with WFPS as the strongest predictor. Negative slope of the CO_2 flux to the WFPS was steeper in T4 than other treatments while positive slope of the nitrous oxide (N_2O) emissions to the CO_2 emission was steeper in T3 and T4 than T1 and T2, implying that 62.2 kg N ha^{-1} yr^{-1} (T3) represents the threshold in changes of WFPS on CO_2 flux and changes of CO_2 emissions on N_2O emissions. GWL had significant effects on WFPS and CO_2 fluxes only during young stage of oil palm (2010 and 2011) ($p<0.05$), which due to the disturbance of capillary rise by the increase of oil palm water uptake. Constant peat decomposition after drainage and compaction would decrease soil porosity and increase WFPS over time which led to decrease in CO_2 fluxes over time. Positive relationship between oil palm yield and WFPS ($p<0.001$) and negative relationship between WFPS and CO_2 fluxes suggest that higher WFPS is better to increase oil palm yield and decrease CO_2 emissions as the palms getting mature. This study suggests that N rates less than 62.2 kg N ha^{-1} yr^{-1} with higher WFPS is better to optimize oil palm yield and reduce CO_2 emissions from tropical peatlands.

Incubation study: Effect of different N rates on peat decomposition under different soil moisture level.

There were no significant differences between CO_2 fluxes in IF and OF (p=0.489) but N_2O fluxes in OF was significantly higher than IF (p<0.001), indicating that N fertilizers most likely leached from IF to OF. Higher slope near oil palm trunk would probably cause fertilizers easily leached to lower slope. The width of circumference fertilizer area was approximately 0.15 m but it was shown that fertilizers affected area would likely to be larger than fertilized area (2 m away from palm) particularly on N_2O emissions. Thus, measurements taken in the fertilized area exclusively likely overestimate actual plot scale emissions induced by fertilization. Thus, the calculation of amount of N fertilizers for incubation study was based on area which was affected by fertilization application where N rates are ten times higher than the average calculated based on field experiment. Results showed that there was no significant effect of N fertilization on cumulative CO_2 and N_2O emissions under 50% WFPS (CO_2; p=0.3670, N_2O; p=0.1689) and 80% WFPS (CO_2; p=0.8865, N_2O; p=0.9032), corresponding with results from field studies. Although N fertilization has been added into the peat soil, C/N ratios in all treatments were still high (>20) which not able to support decomposition explained the insignificant effects of N fertilization on CO_2 and N_2O emissions. Only N_2O emissions from fertilized treatments were significantly affected by soil moisture where cumulative N_2O emissions in 80% WFPS were significantly higher than 50% WFPS in fertilized treatments (p<0.001) which in contrast with field measurements where WFPS more than 70% would decrease N_2O fluxes. These could be due to the presence of plant N uptake in field experiment where higher NO_3^- uptake by oil palm in higher WFPS decreased N_2O fluxes. Positive correlation between CO_2 fluxes and N_2O fluxes were found in both field and laboratory results, suggesting that N_2O emission closely related to peat soil organic matter decomposition. Slope of N_2O emissions to the CO_2 emissions in field experiment was larger than incubation which may due to the presence of plant NO_3^- utilization and likely stimulated root exudation, increasing both CO_2 and N_2O emissions in field. Linear positive relationship was obtained between MBC and GM ($p<0.001$) indicates that greater MBC enhanced gross N mineralization which resulted in higher N_2O production. This study suggests that without N uptake by oil palm, N fertilizers application on tropical peatland would result in larger magnitude of N_2O production in higher soil moisture (80%). However, magnitude of peat decomposition on N_2O emissions would be larger in the presence of plant roots which probably due to utilization of NO_3^- by oil palm roots would likely stimulate root exudation which then stimulate microbial activity.

Conclusions

High C/N ratio (>20) after N fertilizers application explained the insignificant effect of N fertilization on cumulative CO_2 and N_2O emissions in both field experiment and incubation study under 50% WFPS ($p>0.05$), suggesting that quality of organic matter play significant roles in peat decomposition. However, N fertilizers application particularly beyond 62.2 kg N ha^{-1} yr^{-1} resulted in larger effects of GWL on N_2O fluxes, WFPS on CO_2 fluxes and CO_2 emissions on N_2O emissions, implying that N rates less than 62.2 kg N ha^{-1} yr^{-1} would be recommended in an oil palm planted on tropical peatland to mitigate the effects of N fertilization on CO_2 and N_2O emissions but able to optimize oil palm yield. Increased of WFPS with time (>70%) reduced both N_2O and CO_2 emissions and increased oil palm yield, suggesting that bulk density and soil porosity are important for mitigation strategies in cultivated tropical peatland. Significant relationship between GWL and WFPS and CO_2

fluxes were found only during early stage of oil palm showed that water uptake by oil palm plantation would play significant roles in affecting the relationship between GWL, WFPS and CO_2 fluxes. Presence of plant roots are likely affecting the relationship between WFPS and N_2O emissions and relationship between CO_2 emissions and N_2O emissions which need future investigation.

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