SOIL, FERTILIZER AND TOPOGRAPHY AFFECT EMISSIONS OF NITROUS OXIDE AND CARBON DIOXIDE, AND YIELD OF OIL PALM IN INDONESIA AND MALAYSIA

January 2017

ROSNAENI SAKATA

Graduate School of Horticulture

CHIBA UNIVERSITY

(千葉大学審査学位論文)

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および地形が一酸化二窒素と二酸化炭素放出
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Finally, I hope this thesis would give a valuable contribution toward better understanding related with greenhouse gases and oil palm plantation in Indonesia and Malaysia.

General Abstract

Due to increasing of global demand for palm oil, Indonesia and Malaysia are pursuing the expansion of oil palm plantations which is accomplishing considerable concern and debate on global warming as impact of the greenhouse gas emission into the atmosphere. Oil palm plantations as a major contributor on the greenhouse gas emission as related with land use changes had been reported in many research. However, there are still limited studies concerning effect of soil types, fertilizer and topography on nitrous oxide (N_2O), carbon dioxide (CO_2) and yield of oil palm.

These studies were conducted on mineral soil in Tunggal, Indonesia, and in Simunjan, Malaysia and also on peat soil in Tatau, Malaysia. The type of fertilizer application was coated fertilizer and conventional fertilizer. Measurement of N_2O and CO_2 emissions conducted 2 years continuously. The results show that N_2O and CO_2 fluxes showed high variabilities with seasons, soil and fertilizer types. N_2O and CO_2 fluxes in the tropical oil palm plantations were significantly affected by the soil types, but not consistently by fertilizer types.

Since the oil palm plantations have been expanding into the different slope positions, observation the interaction of soil properties and topography influencing greenhouse gas fluxes which are still poorly understood is required. Topography affects

the movement of surface and subsurface water and causes the variability of soil processes, which makes the accurate estimation of greenhouse gas fluxes more difficult. In addition, assessment of the dissolved N_2O concentration as source of indirect emission was also considered. The study result show N_2O and CO_2 fluxes showed variability with seasons and slope positions. Dissolved N_2O concentrations varied by water sources and sampling time, sometimes supersaturated than ambient equilibrated concentration. Therefore, topography effect is needed carefully recognized on estimating the whole gases emissions including the indirect emissions.

Soils and fertilizers are essential factors on the growth and production of oil palm. By applied coated fertilizer by a half and quarter of dosage from conventional fertilizer showed that coated fertilizer was more productively on FFB yields. Consequently, reducing the dosage of coated fertilizer in each soils type showed more productive on FFB yields.

From the above studies, it is important to understand the oil palm plantation on influence toward the greenhouse gas and yield related with the sequence of soil, fertilizer and topography.

インドネシアとマレーシア油ヤシ農園における土壌、肥料および地形が
一酸化二窒素と二酸化炭素放出および収量に与える影響

要約

インドネシアとマレーシアにおいて、栽培面積が急速に拡大している油ヤシ農園は、近年、温室効果ガス一酸化二窒素(N_2O)の発生源として、環境に対する潜在的な影響が注目されている。しかし、土壌タイプや窒素施肥が、N_2O と二酸化炭素(CO_2)生成能に及ぼす影響を検討した例は限られている。そこで本研究では、この２つの要因が、油ヤシ農園からの N_2O と CO_2 放出に及ぼす影響を評価することを目指した。現地の油ヤシ農園において、土壌、肥料および地形が、N_2O と CO_2 放出および収量に与える影響について研究したものである。

本研究は、インドネシアの鉱質土壌の油ヤシ農園と、マレーシアの鉱質土壌と泥炭土壌の油ヤシ農園において実施された。油ヤシ栽培に必須な施肥窒素について、慣行肥料と被覆肥料とで比較して、N_2O と CO_2 放出量を 2 年間継続して測定した。その結果、N_2O と CO_2 放出量が、季節変化や土壌タイプおよび肥料の種類により大きく変動することが示された。被覆肥料区の施肥窒素量は、慣行肥料区の約半分で深層施肥したため、被覆肥料区の施肥窒素あたりの N_2O 放出量は、慣行肥料区を下回る例が見い出された。

油ヤシ栽培は、様々な地形において拡大されている。地形と土壌の特性の相互関係が、温室効果ガスに影響しているか否かについての検討は、まだ限定的

である。地形は、水の流れにより、土壌中の物質変化に影響し、温室ガスの正確な測定は難しくなると考えられた。さらに溶存 N_2O が排出されることに注目することが必要である。研究の結果、N_2O と CO_2 の放出量は、季節と地形によって変動した。そして、溶存 N2O は、水源と水の採取時期によって変化した。

油ヤシの成長と生産のため、土壌と窒素肥料は必須要因である。現地施肥試験では被覆肥料区の施肥窒素量は、慣行肥料区の約半分を施用した。被覆肥料区と慣行肥料区と比べた結果、油ヤシの収量は、被覆肥料の方が生産性が高いことが確認された。土壌型が違っても、被覆肥料の量を減らしても、油ヤシの生産性は高いという結果であった。

上記の研究結果から、油ヤシ農園において土壌、肥料および地形が温室効果ガス放出に重要な影響を与えていることが結論づけられた。

List of Contents

List of Tables

List of Figures

Chapter 1

General Introduction

1.1 Oil palm plantation in Indonesia and Malaysia

Oil palm (*Elaeis guineensis* Jacq.) is a tropical crop and originated from West Africa. In1848, oil palm first planted in Java Island and it had been spread to Southeast Asian plantations development (Henderson and Osborne 2000). Oil palm is important supplier of vegetable oil in the world and one of the most rapidly expanding crops in the tropics. Indonesia and Malaysia had taken over from Nigeria and Zaire in dominating world trade in palm oil since 1966 (Poku 2002). Comparing with others crop-based oil seeds, oil palm trees produces the highest yield per unit area. From 1 ha of oil palm produces average oil yield as 4.09 tonnes, as compared with rapeseed, sunflower and soybean which yields 0.75, 0.5 and 0.37 tonnes, respectively (World Growth 2011). The oil palm tree produces high-quality oil used primarily for cooking in developing countries. It is also used in food products, detergents, cosmetics, and a small extent as biofuel.

From all the worlds, the largest producers of palm oil in the world are still dominated by Indonesia and Malaysia (Fig. 1.1). Since early 1980s, oil palm plantation harvested areas in Indonesia and Malaysia have been increased gradually as shown in Fig. 1.2. In the period 1995-2014, global palm oil production more than tripled from 16.2 million tonnes to 58.8 million tonnes (Fig. 1.3), however during the last three years, production in Malaysia stagnated due to the limited availability of arable land (Product Board MVO 2010).

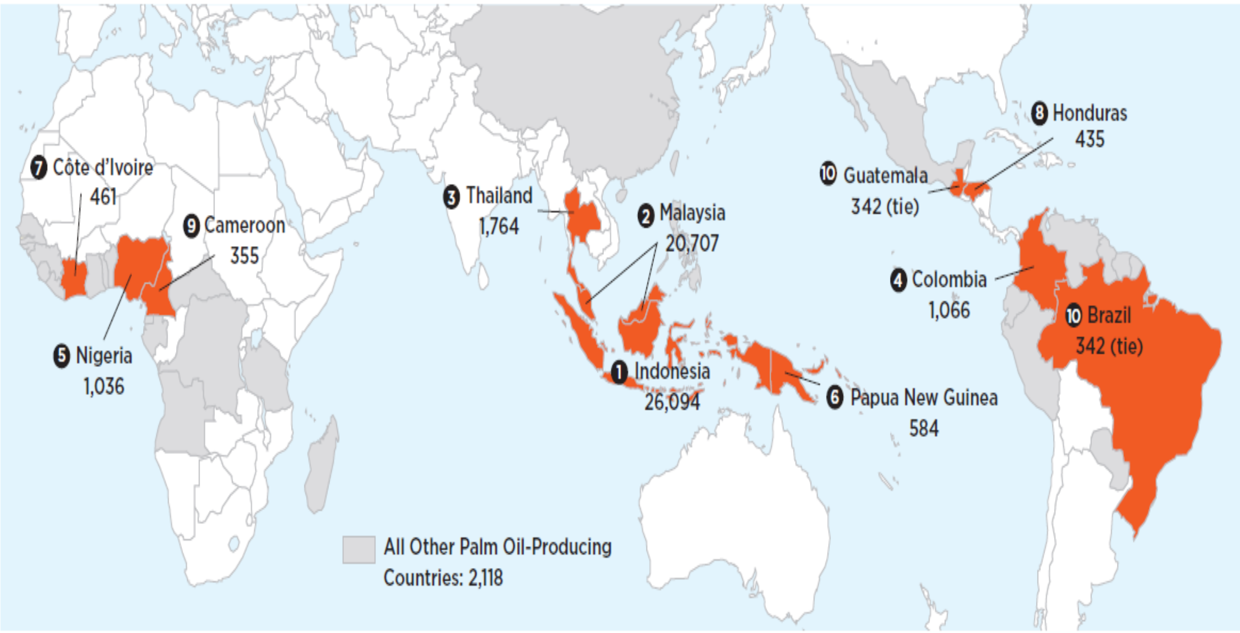


Figure 1.1 Largest producers of palm oil (thousands of tons of oil produced) in 2012 adapted from Union of Concerned Scientist, 2013.

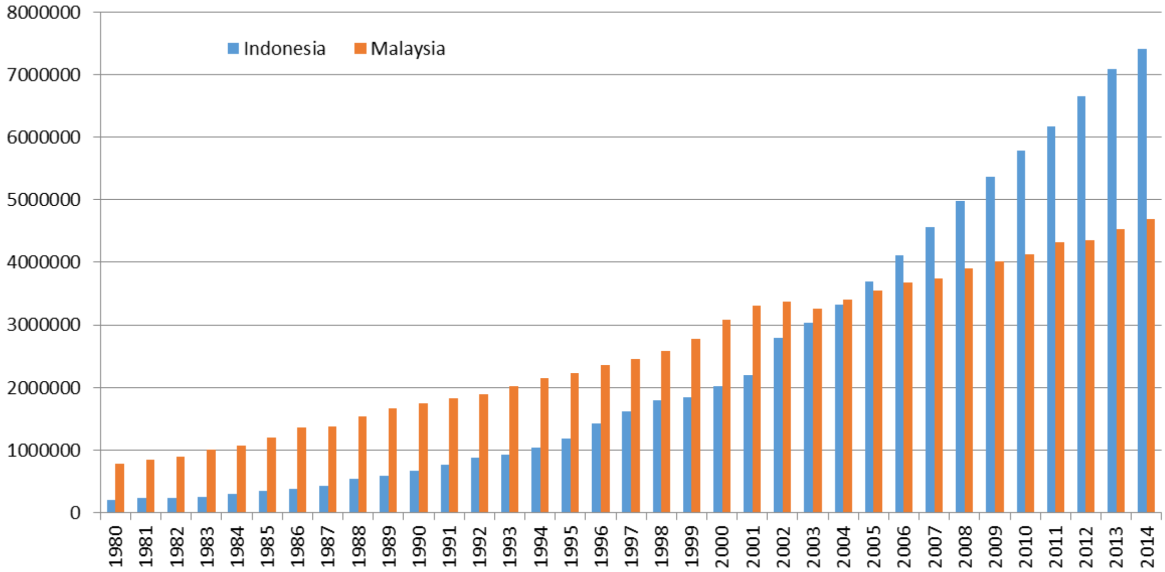


Figure 1.2 Oil palm plantation harvested areas (ha) in Indonesia and Malaysia from 1980 to 2014 (FAO 2014).

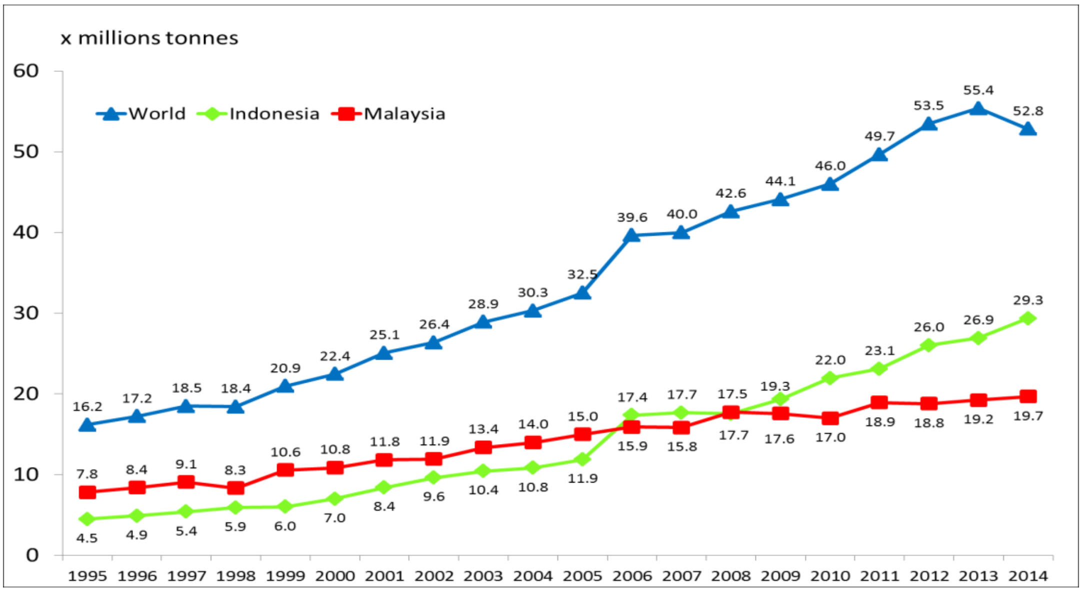


Figure 1.3 Palm Oil productions in the world, Indonesia, and Malaysia (FAO 2014).

In Indonesia, agricultural land is 47.6 million hectares, while total planted areas of oil palm has reach to 10.7 million hectares (IMA 2014). Therefore percentage of oil palm plantation is 22.5% from total agricultural land. Oil palm plantations are largely concentrated in Sumatera. Geographically location of oil palm plantation, Riau province (2.30 million hectares) is positioned as the largest area followed by North Sumatera province (1.39 million hectares). The smallest area of oil palm plantation is located in West Sulawesi province (0.10 million hectares) as shown in Fig. 1.4. Oil palm plantation is approximately 52% owned by private plantations, 39% by smallholders and the rest 8% by government plantations (IMA 2012).

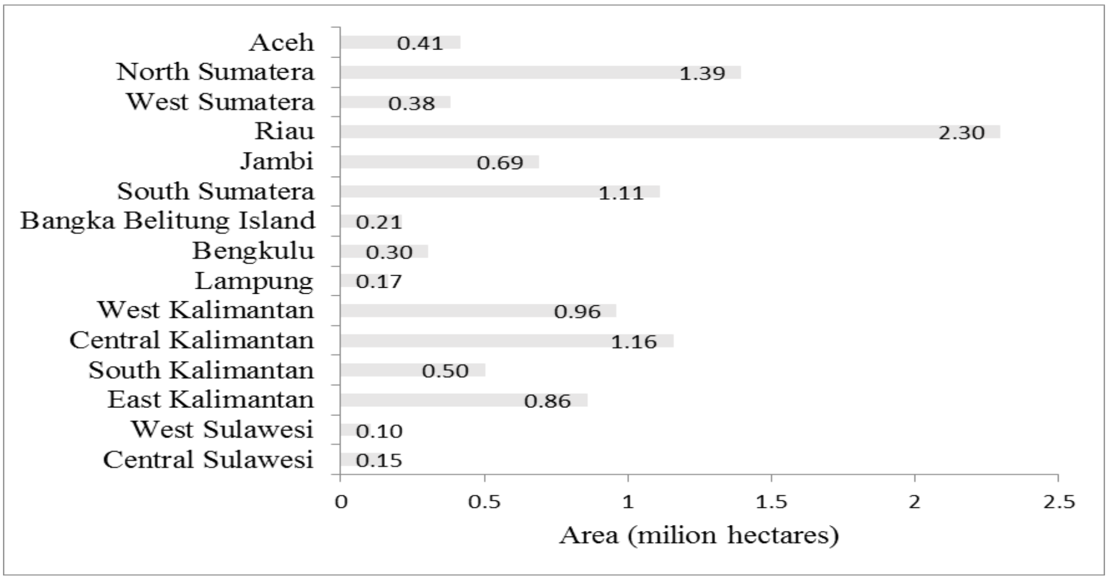


Figure 1.4 Location of oil palm plantations in Indonesia, 2014.

In Malaysia, agricultural land is 7.87 million hectares, while total planted areas of oil palm is 5.39 million hectares (MPOB 2014). Therefore percentage of oil palm plantation is 68.5% from total agricultural land. Oil palm plantation becomes rapid expansion of cultivation area in Sabah and Sarawak. Sabah has the largest plantation areas of 1.51 million hectares, while Sarawak has reached to 1.26 million hectares, as shown in Fig.1.5. The ownership of oil palm plantation as follows, by private estate (61.6%), Federal Land Development Authority (FELDA) (13.9%), Federal Land Consolidation and Rehabilitation Authority (FELCRA) (3.3%), Rubber Industry Smallholders' Development Authority (RISDA) (1.5%), Government or state agency (6.0%), and independent smallholder (13.6%) in 2012 (MPOB 2012).

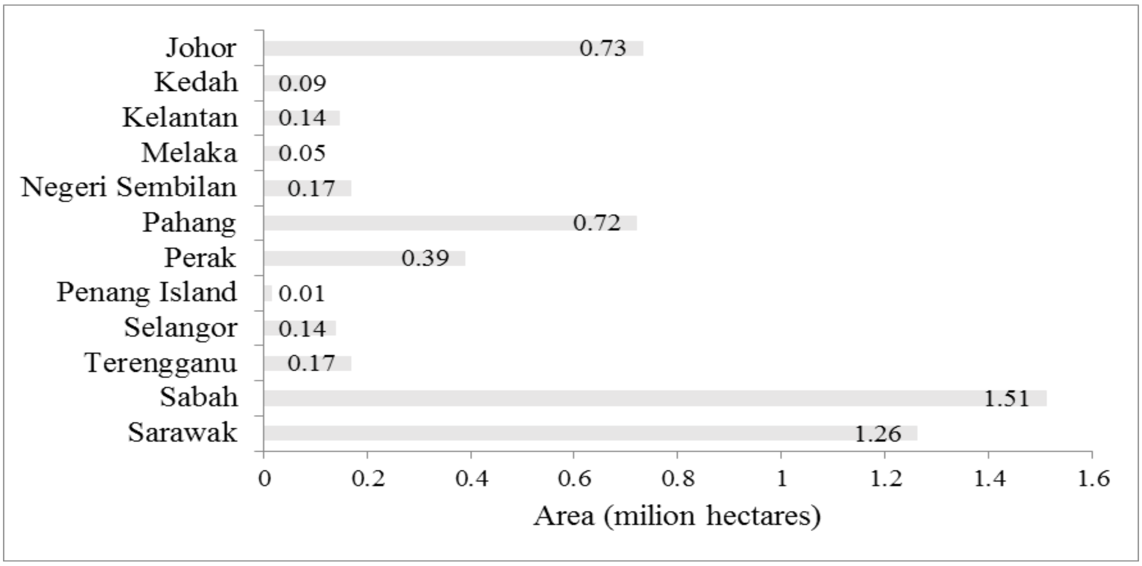


Figure 1.5 Location of oil palm plantations in Malaysia, 2014.

The oil palm is most commonly planted on tropical soils which belong to soil order Ultisols, Oxisols, Inceptisols (Ng 2002) and also in Histosols. In Indonesia oil palm was planted 78% on mineral soil and 22% on peat soil. While in Malaysia, oil palm found 87% on mineral soil and 13% on peat soil. Both in Indonesia and Malaysia, oil palm plantations have been largely extended on peat soil. Oil palm plantations have been extended on peat soil from 418,000 ha in 1990 to 2.43 Mha in 2010. In Indonesia mainly in Sumatera and Kalimantan, oil palm plantation expanded on peat soil as 1.4 Mha (29%) and 307,515 ha (11%), respectively. In Malaysia, expansion of oil palm plantation on peat soil has been reached as 476,000 ha (46%), 215,954 ha (8%), and 29,000 ha (2%) in Sarawak, Peninsular Malaysia, and in Sabah, respectively (Fig. 1.6) (Gunarso *et al.* 2013).

Soil distribution in Indonesia based on soil orders classifications which consist of 10 orders, such as: Inceptisols (31.4%), Ultisols (24.9%), Histosols (12.6%), Entisols (10.4%), Oxisols (9.6%), Alfisols (4.1%), Andisols (2.6%), Spodosols (2.6%), Vertisols (0.9%), and Mollisols (0.9%) in Fig 1.7 (Puslittanak 2000; Sarwani *et al.* 2012). While soil orders in Malaysia are Ultisols and Oxisols (72%), Histosol (20%), and others soil orders (8%) (IBSRAM 1985).

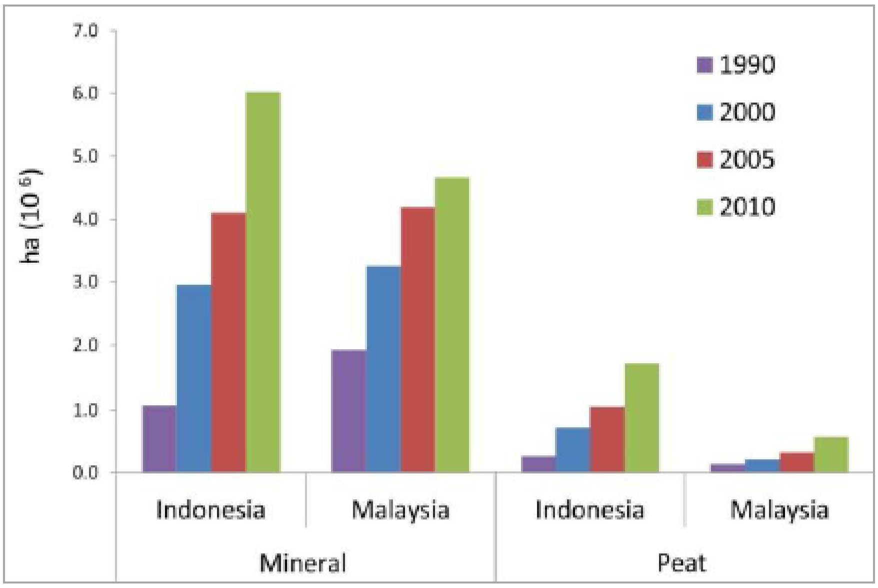


Figure 1.6 Expansion of oil palm plantation on mineral soil and peat soil between 1990 and 2010 in Indonesia and Malaysia

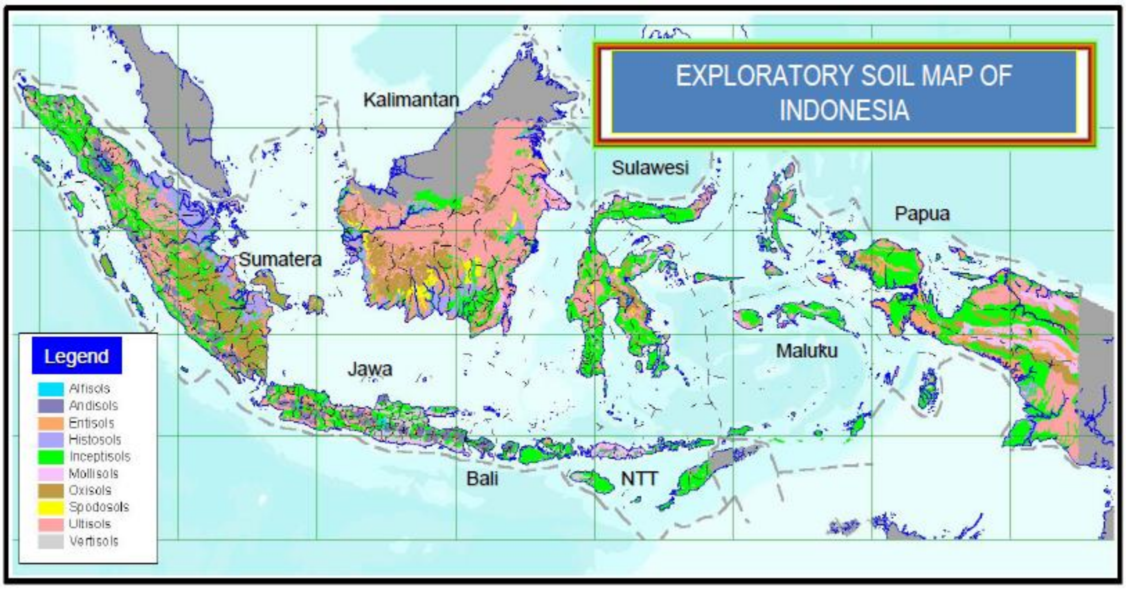


Figure 1.7 Soil distributions in Indonesia based on classification of soils orders (Sarwani *et al.* 2012)

1.2 Agricultural soil as a source of greenhouse gas emission

Agriculture, forestry and other land use sectors are one of significant sources of anthropogenic greenhouse gas emissions (GHGs) that leading to climate change (Fig. 1.8). GHGs are gases in the atmosphere that capture solar radiation and warm the surface of the earth. Increasing concentrations of GHGs can warm the surface of the earth and cause changes in global warming (IPCC 2014). Nitrous oxide (N_2O) emissions come mainly from nitrogen applied to agricultural soils. Methane (NH_4^-) emissions come mostly from the digestive processes of ruminant animals, manure management and rice cultivation. Carbon dioxide (CO_2) emission come mainly from fossil fuel use, production of fertilizers and other agro-chemicals, and soil management.

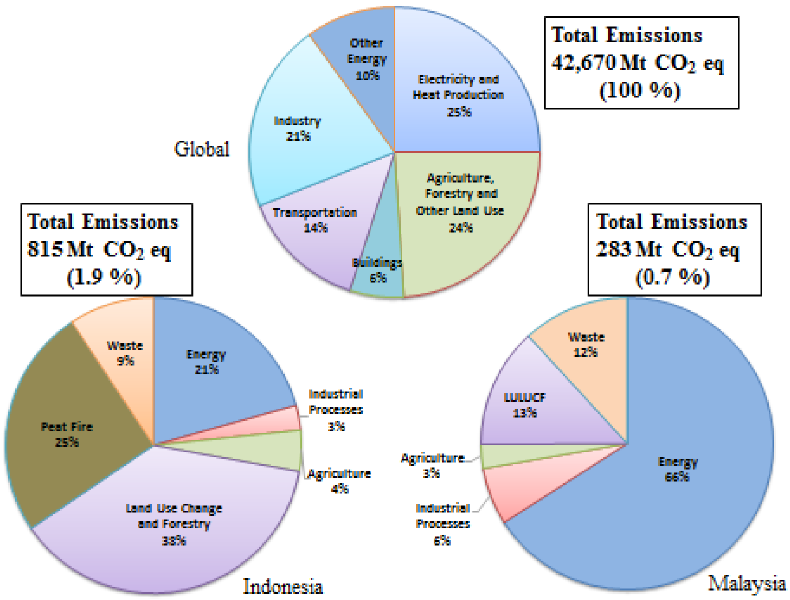


Figure 1.8 Greenhouse Gas Emissions by Sector; LULUCF (Land Use, Land Use Change and Forestry) IPCC (2014); MoE (2010); MoNRE (2010).

Indonesia and Malaysia dominate global production of oil palm, with rapid expansion of plantation area by the conversion of tropical forest and peatlands to oil palm plantation has been focus of debates due to its potential impact on environment (Dewi *et al.* 2009), and emerged as globally significant driver of greenhouse gas emission (Seymour 2014). Over the last 20 years deforestation has been driven predominantly by agricultural expansion, especially of oil palm plantation monocultures (Singh and Bhagwat 2013). Expanding oil palm plantation cause GHGs emissions when the new plantations replaced the forest habitat due to amount of carbon stored in the stems, leaves and roots are small compared with carbon stocks of the natural forest (Wicke *et al.* 2008a). While expansion of oil palm converted from peat soils, it creates two sources of CO_2 emissions, namely emissions due to soil burning and soil drainage. Burning land has been chosen to clear the old vegetation to establish new plantation. Peat soil will burn down into soil profile until it is sufficiently humid to extinguish the fire. Afterwards, upper horizon of peat soil is drained to create suitable soil condition for oil palm. These processes changed the ecological condition of soil biota and leads to gradual oxidation and decomposition of peat matrix, and as a consequence, peat soil release the CO_2 (Agus *et al.* 2009). Expansion of oil palm from forest conversion on mineral soil caused a net release emission of approximately 650 Mg CO_{2eq} ha^{-1}, while on peat soil released over 1,300 Mg CO_{2eq} ha^{-1} during the first 25 year circle of oil palm growth. Emission from peat conversion is even higher due to the composition of drained peat and the resulting emission of CO_2 and N_2O (Germer and Sauerbon 2008). In Indonesia, net annual emissions from land use change and emissions from peat soil link to the expansion of oil palm plantation were reported approximately at 58 Tg CO_2 yr^{-1} (from 1990 to 2000), 65 Tg CO_2 yr^{-1} (from 2001 to 2005), and 127 Tg CO_2 yr^{-1} (from 2006 to 2010). While in Malaysia were estimated at 33 Tg CO_2 yr^{-1} (from 1990 to 2000), 40 Tg CO_2 yr^{-1} (from 2001 to 2005), and 57 Tg CO_2 yr^{-1} (from 2006 to 2010) (Agus *et al.* 2013).

1.3 Nitrogen fertilizers affect environment and yield

1.3.1 Nitrogen fertilizers affect environment

In recent years concern has grown over the contribution of nitrogen (N) fertilizers to the environmental problems. Nitrogen and other nutrients are used inefficiently in most of the world's agricultural systems resulting in enormous and largely unnecessary losses to the environment. According to IPCC (2007), 60% of N fertilizers can be lost as pollutants through leaching of mobile N compounds such as nitrate (NO_3^-) and emission of nitrous oxide (N_2O) as one of potent greenhouse gas.

Once N fertilizers are applied to agricultural systems, the fertilizers are absorbed directly by plants or converted into various other forms through the oxidation process. Excess nitrogen is lost in ionic or gaseous form through leaching, volatilization, and denitrification (Liu 2014). Leaching is the downward movement of N through the soil profile. Water movement in the soil profile can be vertical to groundwater of horizontal to surface drain. Nitrate leaching has negative impact on groundwater quality and it contributes to eutrophication of surface water. Groundwater is very essential source of drinking water, therefore concentration of NO_3^- in the groundwater have a serious consideration. The maximum tolerable concentration of NO_3^- is 10 mg per liter for drinking water. Nitrate exceed that tolerable concentration may present serious health concern is called blue baby syndrome in human infants (WHO 2011; DEQ 2015).

From a greenhouse gas perspective, the fertilizers with the largest effects are the N-based forms that produce N_2O, including ammonium nitrate, ammonium sulphate and urea. According to the Intergovernmental Panel on Climate Change ((IPCC) 2007), 1 kg of N_2O has an equivalent impact of approximately 298 kg of CO_2. N_2O is responsible for 6% of the calculated greenhouse effect caused by human activity. The concentration of N_2O in the atmosphere is increasing at a rate of approximately 0.2% per year (IPCC 2007). N_2O is produced by both the oxidation of ammonium (NH_4^+) to nitrate (NO_3^-) (i.e., nitrification) and the reduction of NO_3^- to dinitrogen gas (N_2) (i.e., denitrification). N_2O is either the by-product (nitrification) or the intermediate product (denitrification) of these processes (Firestone and Davidson 1989). Because of these changes to the N cycling 100-yr lifetime caused by soil disturbance and use of N fertilizers, N_2O emissions from agricultural soils are particularly large, and obtaining reliable estimates is not straightforward (Syväsalo *et al.* 2004). The amount of N_2O released is usually related to N application as organic or mineral fertilizers; a linear relationship between N_2O emission and fertilizer input has been found (Bouwman 1990), and it is dependent on the form in which the N fertilizers are used, the location (i.e., soil type and climatic conditions) and the cultivated crops present (Corre *et al.* 1995; MacKenzie *et al.* 1998; Nagano *et al.* 2012).

There has been a much stronger focus on N_2O emission from soil. However there is another gas from the soil which contributes to pollution of atmosphere, namely nitric oxide (NO). Even though NO indirectly contributes to global warming, NO works to the formation of tropospheric ozone, and the formation of acid rain (McTaggart *et al.* 2002). Generally, N_2O and NO were emitted from all soils by the microbial process of nitrification and denitrification (Bouwman 1990; Granli and Bockman 1994; Smith *et al.* 1997: Pilegaard 2013) by cause of N fertilizer application by increasing available N in the soil. Microbial activity and chemical reactions influence the production and consumption of NO in soil. Nitrifiers and denitrifier are two most significant of micro-organism involved in those processes (Pilegaard 2013).

The net of chemical reaction of nitrification is:

$$\begin{array}{l} \qquad\qquad\quad N_2O\ (gas) \\ \qquad\qquad\quad \uparrow \\ NH_4^+ \rightarrow NH_2OH \rightarrow HNO \rightarrow NO\ (gas) \rightarrow NO_2^- \rightarrow NO_3^- \end{array}$$

While, the net of chemical reaction of denitrification is:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO\ (gas) \rightarrow N_2O\ (gas) \rightarrow N_2\ (gas)$$

The N gases diffuse through the soil pore system and before escaping from the soil to the atmosphere, NO in particular rapidly may be taken up by plants or consumed by microorganisms when the soil water content increased (Firestone and Davidson 1989).

Additionally, Bouwman (1998) showed a model of correlations between water-filled pore space (WFPS) and production of N gases in Fig. 1.9. Generally, both NO and N_2O are produced by same processes, however in opposite to N_2O, production of NO in soils assumes to be nitrification rather than denitrification (Conrad 2002).

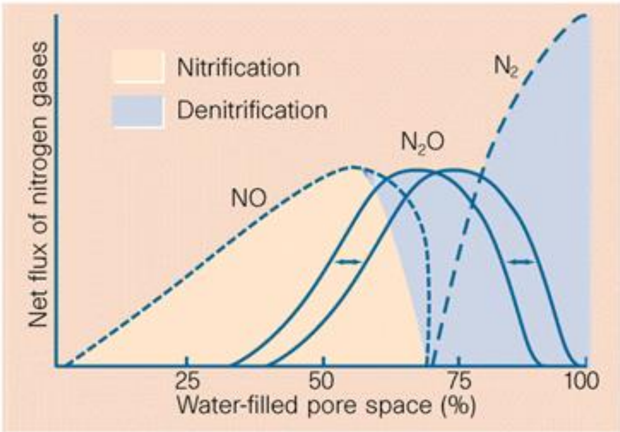


Figure 1.9 Correlation between water-filled pore space (%) and net flux of nitrogen gases (Bouwman 1998).

Conforming to the model, at 30 – 60% WFPS when nitrification is most active, the highest NO fluxes are predicted. The highest N_2O fluxes are expected at 50 – 80% to 60 – 90% WFPS (depending on the soil properties) when denitrification dominates. And at above 80% WFPS when oxygen becomes so limited that N_2O is consumed by denitrification and N_2 becomes the main end product (Bouwman 1998; Pillegard 2013).

In the agriculture land, topography affects the movement of surface and sub-surface water (Hairston and Grigal 1994; Hirobe *et al*. 1998). Topography has been demonstrated large temporal and spatial variability factor of soil processes which influence the accurate estimation and prediction of the N_2O and CO_2 gases exchange (Brito *et al.* 2009; Werner *et al.* 2007a). Effect of topography on N_2O and CO_2 gas emissions reported not only in temperate ecosystems but also in tropical areas (Fang *et* *al.* 2009). A significant amount of N_2O emissions originates from agricultural soil as direct emission and from aquatic systems as indirect emission (Mosier *et al.* 1998). Indirect N_2O emissions are estimated from N leaching in agro-ecosystems.

1.3.2 Nitrogen fertilizers affect yield

The oil palm is a heavy feeder and requires quite large quantities of fertilizers especially with N fertilizer to produce good yield (Comte *et al.* 2012) and optimum economic return (Ahmad 2000). Fertilization is one factor as most contributors which accounting for 29% of the yield increment. Requirements of N are up to 1.2 kg N per palm per year has been recorded (Kwan 1998). It is reported that applications of nitrogen fertilizer and Fresh Fruit Bunch (FFB) production of oil palm on mineral soils have a linear correlation. FFB production increased with increasing amount of N fertilizer rate (Khasanah *et al*. 2012). Approximately 18.8 t ha^{-1} yr^{-1} FFB productions were produced from the application of 141 kg N ha^{-1} yr^{-1} of N fertilizer application. N rates should be higher where planting density are low (112 – 128 palm ha^{-1}) and usually lower when planting density are high (138 – 148 palm ha^{-1}) (Von Uexkull and Fairhurst 1991). FFB yields are attained peak yield earlier at between 8 and 10 years after planting. However, FFB yield will usually decline 16 year after planting, due to increasing difficulty in harvesting and need to maintain number of fronds for better harvesting efficiency (Goh and Teo 1997). Any difference in FFB yield responses are depends on climate, soil condition, fertilization, uptake and demand of nutrient. Nutrient uptake rate is generally influenced by root length, soil nutrient concentration and soil water content, and nutrient demand is dominated by oil palm growth and production (Tinker and Nye 2000). Therefore, it is necessary to ensure that the oil palm is planted on suitable land and keep maintain on fertilizer management to gain high oil palm yield.

1.3.3 Nitrogen fertilizer types

N is important plant nutrient in biochemical process and affects very important physiological process such as photosynthesis which in turn affects growth and yield of palm. Oil palm requires four macronutrients from fertilizer such as nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg). N fertilizers namely ammonium nitrate (26% N), ammonium sulphate (21% N), ammonium chloride (25% N), urea (46% N), blended NPK, NP and PK are commonly used as a form of conventional fertilizer. While rock phosphates (27-34% P_2O_5), muriate of potash (MOP, 62% K_2O), for kieserite or magnesium sulfate (17% Mg; 23% S), sodium borate are also used (FAO 2005; Gerendas and Heng 2010). Currently, urea and urea based fertilizers mostly used for oil palm to its high N content and low price (Zakaria and Tarmizi 2007). However, conventional N fertilizer is easily be released and lost during its biochemical transformation in the soil, water and atmospheric system. Tremendous loss of N from conventional fertilizer decreased yield and brought negative impact on the environment by leaching, volatilization and nitrous oxide emissions.

Considering the problem of conventional N fertilizer, Shoji and Gandeza (1992) reported the practical application to increase the efficiency of fertilizer by introducing the concept of controlled release fertilizer. One type of controlled release fertilizer is coated urea, Meister (41-42% N). Meister is used as raw materials of blended fertilizer, since it is a straight fertilizer containing only nitrogen. It is mixed with phosphate, potassium, microelement, ammonium fertilizer granules (Sakamoto 2012). Coated fertilizer is required to avoid N loss through leaching, volatilization, and denitrification. Coated fertilizer inhibits the N loss and serve to release N in a mode that is compatible with the metabolic requirements of plants. Coated fertilizer is basically determined by blending water permeable and water impermeable resins and surfactants. The release rate is primarily governed by soil temperature and is hardly affected by other soil conditions. Application of coated fertilizer in agriculture is great because of such advantages as labor saving, increased nutrient efficiency, improved yield, and reduced negative environmental effects (Trenkel 1997).

N fertilizer additive which has potentially effective for N loss and reducing of N_2O emissions is nitrification inhibitors. Nitrification inhibitors are chemicals that slow down or delay the nitirification process, thereby decreasing the possibility the large losses of nitrate will occur before the fertilizer nitrogen is taken up by the plants (Nelson and Huber 2001). Nitrification inhibitors have used in the field to improve the efficiency of fertilizers and to reduce both nitrate leaching and denitrification by maintaining the N in the soil as NH_4^+. Dicyandiamide (DCD) act as a nitrification inhibitor by inhibing the first stage of the nitrification process, the oxidation of NH_4^+ to NO_2^-, and rendering bacterial enzymes ineffective. Therefore DCD can regarded as a slow release N fertilizer (containing about 65% N) (Di and Cameron 2006; Jumadi 2008b).

The development of innovative technologies plays an important priming effect of the extensive fertilizers use for agriculture. The potential benefit from any kind of fertilizers application depends on a number of site-specific, such as soil type, climate, cultural practices, and N management program.

1.4 Objective of studies

Global demand for palm oil is expected to increase and the expansion of oil palm plantations raises environmental concern. Assessments to develop alternatives relating to soil, fertilizers and topography are necessary to improve high value of oil palm more environmentally compatible (Fig. 1.10). Therefore, objectives of studies as below:

1. To determine effect of soil types and N fertilizers on emissions of greenhouse gases, N_2O and CO_2 under tropic oil palm.
2. To determine effect of topography to control spatial variation on N_2O and CO_2 emission and to assess dissolved N_2O concentration as a source of indirect emission under tropic oil palm.
3. To determine effect of conventional and coated fertilizers on fresh fruit bunch (FFB) yield in different soil types under tropic oil palm.

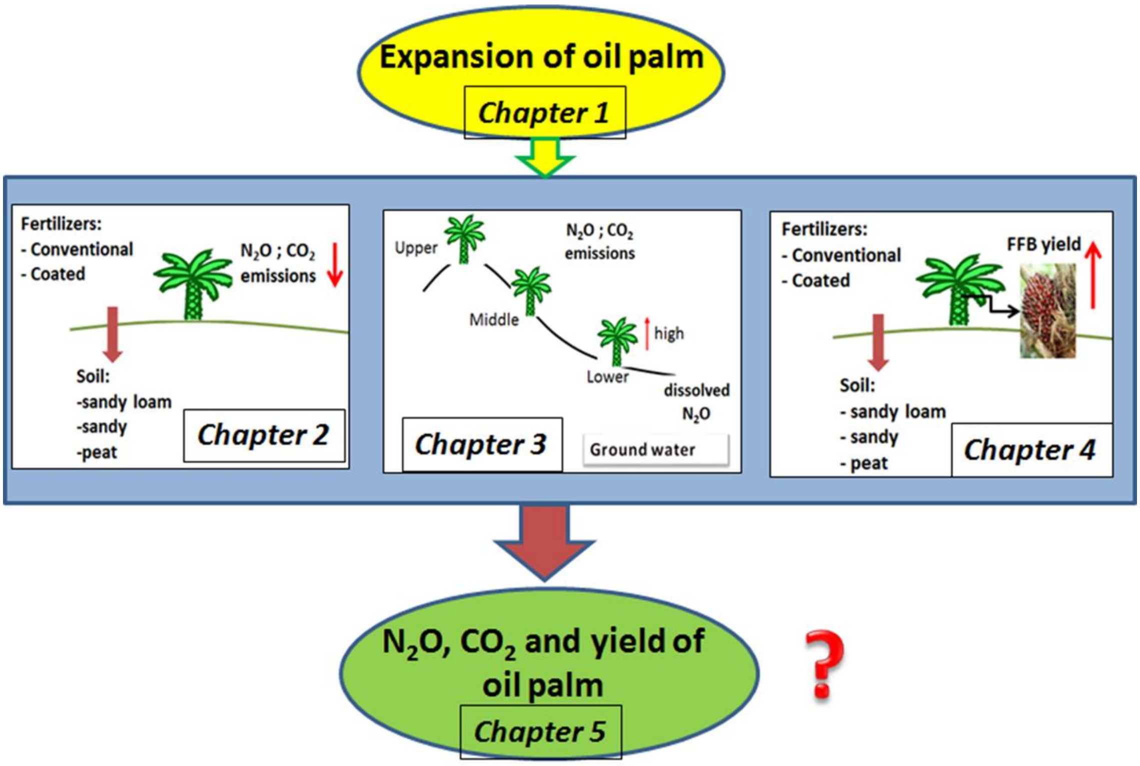


Figure 1.10 Framework of studies showing effect of soil, fertilizer and topography on N_2O, CO_2, and yield of oil palm.

Chapter 2

Effect of soil types and nitrogen fertilizer on nitrous oxide and carbon dioxide emissions in oil palm plantations

2.1 Abstract

Oil palm (*Elaeis guineensis* Jacq.) production in Indonesia and Malaysia is currently the focus of concern due to its potential impact on the environment via greenhouse gas emissions. Oil palm plantations have been reported to release large quantities of nitrous oxide (N_2O) into the atmosphere, which is most likely linked to nitrogen (N) fertilizer use. However, there are still limited studies comparing effects of the type of soil and N fertilizer on N_2O and carbon dioxide (CO_2) emissions. This study aimed to evaluate the effects of soil types and N fertilizer on N_2O and CO_2 emissions in oil palm plantations. N_2O and CO_2 emissions were measured for 15–16 months from 2010–2012 in Tunggal sandy loam soil, Indonesia, and in Simunjan sandy soil and Tatau peat soil, Malaysia. Within each site, treatments with coated fertilizer and conventional fertilizer, and unfertilized with and without tillage, were established. N_2O and CO_2 fluxes showed high variabilities with seasons, types of soil and fertilizer treatments. The mean of the N_2O fluxes from each treatment in the Simunjan sandy soil was the lowest among the three soils, ranging from 0.80 to 3.81 and 1.63 to 5.34 μg N m^{-2} h^{-1} in the wet and dry seasons, respectively. The mean of the N_2O fluxes from each treatment in the Tunggal sandy loam soil ranged from 27.4 to 89.7 and 6.27 to 19.1 μg N m^{-2} h^{-1} in the wet and dry seasons, respectively. The mean of the N_2O fluxes was found to be the highest among the three soils in each treatment of the Tatau peat soil, ranging from 131 to 523 and 66.1 to 606 μg N m^{-2} h^{-1} in the wet and dry seasons, respectively. The N application rate of coated fertilizer was about half that of conventional fertilizer and was applied as deep placement. In the Tunggal soil, coated fertilizer reduced N_2O emissions by 31 and 48% in wet and dry seasons, respectively, compared to the conventional fertilizer, and was similar to unfertilized treatment. However, N_2O emissions increased in Simunjan and Tatau soils during dry seasons. There was no significant difference between treatments. These results show that N_2O and CO_2 fluxes in the tropical oil palm plantations were significantly affected by the type of soil, but not always by fertilizer treatments.

Key words: N fertilizer, N_2O and CO_2 fluxes, sandy loam, sandy, peat soil.

2.2 Introduction

Carbon dioxide (CO_2) and nitrous oxide (N_2O) account for 76 and 6% of the total anthropogenic greenhouse gas (GHG) emissions, respectively, at different values of global warming potentials (Rogner *et al.* 2007; IPCC 2014). Based on limited study, the largest anthropogenic source N_2O emissions was from agriculture which accounts for 67%. Agriculture contributed direct and indirect emissions. Fertilizer and livestock manure as direct emissions contributed 42%, and runoff and leaching of fertilizer as indirect emissions contributed 25% (IPCC 2007). However, agricultural soils besides as a source, also as a sink for carbon and nitrogen (N) gases (Bouwman *et al.* 1995).

Oil palm plantations have been reported to release large quantities of N_2O into the atmosphere, which is most likely linked to N fertilizer use. When examining the GHG emissions among land uses in Jambi, Sumatra Island, Indonesia, Murdiyarso *et al.* (2002) found that oil palm plantations released large quantities of N_2O into the atmosphere. N fertilizer, by increasing N availability, plays a significant role in soil carbon sequestration by increasing crop biomass and by influencing the microbial decomposition of crop residue (Green *et al.* 1995; Lal 2004). The emission factor (EF, i.e., the ratio of N_2O-N emission to input of N fertilizer) is often estimated using the default IPCC value as 1% for mineral soil, but 16% for tropical organic soil (peat soils)

(IPCC 2006). However, there are large variations in EF due to differences in environment, crops and management.

Although applications of N fertilizer consistently increase crop biomass, its effect on soil carbon content varies with the type of soil (Alvarez 2005), which affects the flux of CO_2 into the atmosphere. Soils in tropical ecosystems emit far more N_2O than soils in other terrestrial ecosystems (Sanhueza *et al.* 1990). Because of the variability in soil types and soil moisture, some tropical soils emit more N_2O than others. Puerto Rican Vertisol has been reported to have an EF of approximately 4%, which is five times what is reported for unfertilized fields (Mosier and Delgado 1997). Studies on tropical peat soils have established that emissions of N_2O are related to both season and land use changes (Hadi *et al.* 2000; Inubushi *et al.* 2003). However, studies that compare the effect of soil types with N fertilizer, in relation to N_2O and CO_2 emission rates, are still limited. Coated fertilizer is one of fertilizer forms that have been reported to reduce N_2O emission rate by effectively controlling the release of NH_4^+, which caused a prolonged production period of NO_3^- in Japanese Andosol (Hou *et al.* 2000; Amkha *et al.* 2009). In imperfectly drained Gleysol, N release from coated fertilizer matches with plant demand and N use efficiency increase, and the resulting low NO_3^- concentration would be expected to limit denitrification, providing an explanation for the low N_2O fluxes

(Akiyama *et al.* 2009). Coated fertilizer releases an adequate amount of N to meet the crop's N requirement at various growth stages and enhance the N uptake by deep-side placement in clayey and sandy paddy soil (Acquaye and Inubushi 2004).

In this study, over a period of more than a year, the emissions of the greenhouse gases N_2O and CO_2 evaluated from oil palm plantation fields in Indonesia and Malaysia, across three types of soil (sandy loam, sandy and peat soil) in response to treatments of N fertilizer application.

2.3 Materials and Methods

2.3.1 Site descriptions and treatments

Study sites were located in oil palm plantation areas on tropical land, with one site in Indonesia and two sites in Malaysia (Fig. 2.1). The first site was located in Tunggal Plantation, Riau Province, Indonesia (S00°20.731', E102°17.617') on sandy loam soil classified as Ultisols [according to the United States Department of Agriculture (USDA) Soil Taxonomy]. The Tunggal Plantation site has a sloping topography with an annual rainfall of 1387 mm. The second site was located in Simunjan Plantation, Sarawak, Malaysia (N01°03.958', E110°51.798') on sandy soil, which was also classified as Ultisols. The Simunjan Plantation site is characterized by sloping topography with an annual rainfall of 4095 mm. The third site was located in Tatau Plantation, Sarawak, Malaysia (N02°57.924', E112°45.851') on peat soil, classified as Histosols. The Tatau Plantation site is characterized with a flat topography, located along the coast, with an annual rainfall of 2225 mm. Three replications of the following four experimental treatments were conducted:

Treatment B: no nitrogen fertilizer and no tillage.

Treatment B2: no nitrogen fertilizer, with tillage only in the soil (0–15 cm).

Treatment C: conventional fertilizer (non-coated) surface application on four spots approximately 140 cm away from palm trees, with no tillage.

Treatment M: coated fertilizer in granular form was applied by the deep placemen method: namely, after digging soil to 0–15 cm depth at four different spots, approximately 140 cm away from palm trees, fertilizer was incorporated and covered with soil.

Except for B and B2 treatments, the annual rates (kg N ha^{-1}) of application for the conventional fertilizer were 151 as NPK (Nitrogen-Phosphorous-Potassium) (16-4-25), 107 in the first year and 121 in the second year as NK1 (1:1 mixture of ammonium sulphate and MOP (Muriate of Potash)), and 69 as urea in Tunggal, Simunjan and Tatau, respectively. The rate of conventional fertilizer application followed each plantation's guidelines. It was considered that the coated fertilizers are more efficient due to a lower loss rate of N (Shoji and Kanno 1994). Hence, the rates of application for the coated fertilizer were about half the rate of the conventional fertilizers, namely 76, 62 and 46 kg N ha^{-1} in Tunggal, Simunjan and Tatau, respectively. As indicated in Fig. 2.2–2.4, solid arrows and dashed arrows indicate conventional and coated fertilization times, respectively. In Tunggal, fertilizers were applied once each in the wet season and dry season for both conventional and coated fertilizer. In Simunjan, fertilizers were applied twice for conventional fertilizer and once for coated fertilizer in the first wet season, once for both conventional and coated fertilizer in the dry season, and once for both conventional and coated fertilizer in the second wet season. In Tatau, fertilizers were applied twice for conventional fertilizer and once for coated fertilizer in the first wet season, once for both conventional and coated fertilizer in the dry season, and once for coated fertilizer in the second wet season.

Physicochemical analysis of the soil samples both undisturbed soil cores and composite soil samples were collected from the three replications from the 0–10 cm soil depth. The soil samples were analyzed for their physical and chemical properties. Prior to analysis, the soil samples were maintained at 4°C. The undisturbed soil cores were measured for soil volume using a three-phase meter (DIK-1130, Daiki Rika Kogyo Co.

Ltd). The core samples were weighed and oven dried at 105°C for 48 h. After drying, the core samples were reweighed to calculate soil moisture content, bulk density (BD) and water-filled pore space (WFPS). Soil particle size distribution was determined by the Bouyoucos hydrometer method (Kroetsch and Wang 2008). Soil samples were air dried and passed through a 2-mm sieve, and the sieved soil was extracted with potassium chloride (KCl) solution at a 1:2.5 soil-to-solution ratio. The resulting soil suspension was shaken for approximately 1 h before filtration through filter paper. The soil pH was measured with a glass electrode pH meter (D-52, Horiba Co., Ltd). Total carbon and nitrogen contents were determined using a Carbon and Nitrogen Analyzer (CN corder; MT-700 Yanaco Analytical Industry Co., Ltd). The inorganic N contents of NH_4^+ and NO_3^- were determined by sieving fresh soil through a 2-mm sieve, extracting it in 1 M KCl, and using the nitroprusside method (Anderson and Ingram 1989) and hydrazine reduction method (Hayashi *et al.* 1997), respectively. To investigate the effect of soil water on N_2O and CO_2 productions, soil moisture was monitored and recorded using a Watermark and Sensor TR-0306 (equipped with a stainless steel protective tube) connected to a Thermo Recorder (TR-71Ui; T&D Corporation). The device measures the soil moisture tension (pF unit) to indicate soil moisture level. The lower the reading the higher soil moisture content, and conversely, the higher the reading the lower the moisture content (Tan 1996). Soil temperature was measured and recorded using a thermo sensor (203AT; T&D Corporation) with a thermo recorder at 10 cm soil depth. Every 3 months, the recorded data were downloaded to a computer. The precipitation data were collected by oil palm plantation staff members using rain gauges located within the oil palm plantation areas.

2.3.2 Measurement of N_2O and CO_2 fluxes

Measurement of N_2O and CO_2 fluxes was conducted at 2-week intervals over a period of 15 months from December 2010 to February 2012 at Simunjan and Tatau Plantations and over a period of 16 months from March 2011 to June 2012 at Tunggal Plantation. Gas sampling was consistently conducted at mid-morning. N_2O and CO_2 fluxes were determined by placing a 20.8 cm diameter and 14.2 cm height PVC pipe chamber driven to a depth of 5 cm into the soil at approximately 1 m distance from the palm tree's trunk (Handayani *et al.* 2010) in the area under the shade of the palm tree canopy. The chamber was replicated at three different places at least 10 m apart at each treatment site, and included the fertilized spot. Gas samples were taken from each chamber, after stabilizing the chamber for 5 min, using a 30-mL gas syringe with tubes connecting to the chamber. Gas samples were collected at 0-, 10- and 20-min intervals and were injected into glass vials that had been evacuated and closed tightly with a butyl rubber seals. The filled vials were transported to the laboratory, where N_2O and CO_2 fluxes were measured by a gas chromatograph (GC-14B, Shimadzu, Japan) equipped with an electron capture detector (ECD) and thermal conductivity detector (TCD), respectively. The emission factor (EF) was calculated using cumulative N_2O fluxes to determine the percentage of N_2O-N emitted for each fertilizer treatment (Dobbie and Smith 2003a; Jumadi *et al.* 2008). The emission factor (EF) was calculated using the following formula:

$$EF (\%) = (M-B2)/N \times 100 \text{ or } (C-B)/N \times 100 \qquad (1)$$

where M and C are the cumulative N_2O fluxes emitted from coated fertilizer and conventional fertilizer treatment (kg N_2O-N ha^{-1} $period^{-1}$), respectively; B2 and B are the cumulative N_2O fluxes (kg N_2O-N ha^{-1} $period^{-1}$) emitted from non-N fertilizer treatment with and without tillage, respectively.

2.3.4 Statistical analysis

The significance of the cumulative N_2O and CO_2 fluxes for each treatment and study site were analysed using a two-way analysis of variance (ANOVA) test. The relationship between N_2O and CO_2 emissions were analysed using linear regression.

Means of N_2O and CO_2 fluxes for each treatment and study site during wet and dry seasons were analysed using a three-way ANOVA test. Correlations between gas emission and soil physicochemical properties among the study sites were analysed using Pearson's correlation. Statistical considerations were based on $p < 0.05$ and $p < 0.001$ significance levels. Statistical analyses were conducted using IBM SPSS Statistics 21.

2.4 Results

2.4.1 Physicochemical soil properties of study sites

The physicochemical properties of the three soil types were varied (Table 2.1). In Tunggal and Simunjan, both were mineral soils with different particle size distributions. Sand content was higher in Simunjan than in Tunggal, while clay and silt contents were higher in Tunggal than in Simunjan. Other soil parameters such as NO_3^-, NH_4^+, total N, total carbon and WFPS were higher in Tatau peat soil than the other two mineral soils. Soil pH and BD were lower in the Tatau peat soil than in the other two mineral soils. Soil N_2O emission for Tunggal, Simunjan and Tatau are shown in Fig. 2.2, 2.3 and 2.4, respectively. In Tunggal sandy loam soil, it was observed that there were high N_2O fluxes (279–581 μg N m^{-2} h^{-1}) during the wet season, especially after the first fertilization, and high precipitation, which gradually declined thereafter. The peak of N_2O fluxes appeared again after a heavy precipitation in the second wet season (Fig.

2.2). In the Simunjan sandy soil, N_2O fluxes were lower (up to 52.5 μg N m^{-2} h^{-1}) than in the Tunggal sandy loam soil, but peaks were observed after heavy rains not only in the wet season, but also in the dry season (Fig. 2.3). N_2O fluxes in the Tatau peat soil were higher and more variable (up to 1022 μg N m^{-2} h^{-1}) than the fluxes in the two mineral soils during the study period, and only in treatment M, N_2O fluxes were highest in the dry season, but the N_2O fluxes in the other treatments were higher in the wet seasons (Fig. 2.4).

During the study period, N_2O fluxes varied across all study sites and treatments (Table 2.2). Across all the study sites, the mean of N_2O fluxes in the Simunjan sandy soil was lowest, ranging from 0.80 to 3.81 and 1.63 to 5.34 μg N m^{-2} h^{-1} in the wet and dry seasons, respectively. The mean of N_2O fluxes in the Tunggal sandy loam soil ranged from 27.4 to 89.7 and 6.27 to 19.1 μg N m^{-2} h^{-1} in the wet and dry seasons, respectively. The mean of N_2O fluxes was highest in the Tatau peat soil among the three soils, ranging from 131 to 523 and 66.1 to 606 μg N m^{-2} h^{-1} in the wet and dry seasons, respectively. Coated fertilizer reduced N_2O emission by 31 and 48% in wet and dry seasons, respectively, compared to conventional fertilizer, and almost equaled the unfertilized treatment only in the Tunggal soil, but increased in Simunjan and Tatau soils in dry season. Three-way ANOVA for each treatment and study site during wet and dry seasons determined that there were statistically significant differences in means of N_2O fluxes among the study sites (p = 0.000), sites and treatments (p = 0.038), treatments and seasons (p = 0.053) and combination factor of sites, treatments and seasons (p = 0.020) (Table 2.2). The cumulative N_2O fluxes are summarized in Table 2.3. Cumulative N_2O fluxes ranged from 0.59 to 4.09, 0.11 to 0.42 and 11.1 to 42.7 kg N ha^{-1} $period^{-1}$, in Tunggal sandy loam soil, Simunjan sandy soil and Tatau peat soil, respectively. Results indicated the highest cumulative N_2O fluxes in the Tatau peat soil and the lowest cumulative N_2O fluxes in Simunjan sandy soil. Two-way ANOVA analysis determined that there were statistically significant differences in cumulative N_2O fluxes among the study sites (p = 0.000), though no significant difference was found in the treatments within each study site (p = 0.125) (Table 2.3). Among the three study sites, the N_2O emission factors were significantly affected by sites (p = 0.000), fertilizer treatment, i.e., use of conventional and coated fertilizer (p = 0.038), and interaction of the sites and fertilizer treatments (p = 0.010) (Table 2.4). EF for the conventional and coated fertilizer applications showed significantly positive correlation with the soil parameters such as NO_3^-, NH_4^+, total N, total carbon and WFPS, and has a significantly negative correlation with the soil pH and BD (Table 2.5).

2.4.2 Soil CO_2 emission

CO_2 fluxes are presented in Fig. 2.2, 2.3 and 2.4 for Tunggal, Simunjan and Tatau, respectively. During the study period, CO_2 fluxes varied across all the study sites and treatments (Table 2.6). The mean of the CO_2 fluxes in the Tunggal sandy loam soil ranged from 45.5 to 56.8 and 56.4 to 96.5 mg C m^{-2} h^{-1} in wet and dry seasons, respectively. The mean of the CO_2 fluxes in the Simunjan sandy soil ranged from 71.1 to 114 and 104 to 134 mg C m^{-2} h^{-1} in wet and dry seasons, respectively. The mean of the CO_2 fluxes was found to be the highest in the Tatau peat soil, ranging from 89.8 to 223 and 92.7 to 208 mg C m^{-2} h^{-1} in wet and dry seasons, respectively. Three-way ANOVA for each treatment and study site during wet and dry seasons determined that there were statistically significant differences in means of CO_2 fluxes by effect of study sites only (p = 0.000) (Table 2.6). In Tatau peat soil, as the soil temperature decreased, the soil CO_2 fluxes tended to increase. However, these CO_2 fluxes included both soil and root respiration, but these values might be underestimated due to relatively long closure time, as 20 minutes. Cumulative CO_2 fluxes ranged from 5302 to 7971, 7638 to 11431 and 8797 to 16949 kg C ha^{-1} $period^{-1}$, in Tunggal sandy loam soil, Simunjan sandy soil and Tatau peat soil, respectively (Table 2.7). Among the three study sites, the cumulative CO_2 fluxes were the highest in Tatau peat soil and the lowest in Tunggal sandy loam soil. For cumulative CO_2 fluxes, there was a statistically significant difference among the study sites (p = 0.000) but no significant difference in the treatments at each study site (p = 0.064).

Soil N_2O and CO_2 fluxes showed significantly positive linear relationship and varied among the study sites (Fig. 2.5). Variability observed in N_2O emission explained by 2.71%, 7.19%, and 38% soil CO_2 emission in Tunggal sandy loam soil, Simunjan sandy soil, and Tatau peat soil, respectively.

2.5 Discussion

2.5.1 N_2O fluxes and EF correlated with soil and fertilizer types

In Tunggal sandy loam soil, the highest N_2O fluxes were measured in the wet season, March 2011 (Fig. 2.2). High peaks of N_2O flux were observed 1 week after the first fertilizer application in both conventional fertilizer and coated fertilizer treatments, and also during high precipitation and soil moisture content at the site. As reported by Clayton *et al.* (1994) and Webb *et al.* (2004), increased N_2O fluxes after N fertilization are not unusual and often show a marked response to precipitation events. The results also showed that N_2O fluxes increased after N fertilization, reached a peak, then decreased rapidly before levelling off after approximately 1 to 2 weeks. Subsequently,

N_2O fluxes gradually decreased before sharply increasing again in December 2011 with both high precipitation and soil moisture. In Simunjan sandy soil, high N_2O fluxes were shown twice in the wet season and one time in the dry season when precipitation was high (Fig. 2.3). Increased fluxes during these periods coincided with high precipitation events for 2–3 weeks in duration. Similar results were reported in Minnesota loamy sand in which irrigated potato fields fertilized with polymer-coated urea exhibiting increased fluxes in response to high precipitation events (Hyatt *et al.* 2010). Changes in the soil moisture content after the precipitation event presumably influenced soil porosity, consequently increasing the probability of denitrification and diffusion of N_2O out of the soil (Inubushi *et al.* 1996). During the study period, there were negative N_2O emissions that may be explained by a decrease in gas diffusivity, leading to increased microbial consumption of N_2O and denitrification before emission (Arah *et al.* 1991). Although production rates of N_2O are usually larger than consumption rates, stressed soils that are usually considered as net sources of atmospheric N_2O can temporarily become a sink (Minami 1997; Inubushi *et al.* 2003). In Tatau peat soil, fluxes of N_2O were higher than those in sandy loam and sandy soils. Although the pattern of N_2O fluxes varied during the study period, the coated fertilizer application remained high throughout the study period (Fig. 2.4). N_2O emissions were particularly high when fertilizer was applied to wet peat soil. N_2O emissions from fertilized tropical agricultural peat soils are high, sometimes even extremely high, especially under humid climate and organic carbon-rich soil conditions (Williams *et al.* 1999). The variation in N_2O fluxes is generally relative to the rates of denitrification affected by moisture content and the quantities of NO_3^-, NH_4^+ and carbon substrates in soil (Clayton *et al.* 1994; Couwenberg 2009).

Effect of soil water toward the N_2O emission explained by Schindlbacher *et al.* (2004), N_2O emissions increased with decreasing water tension or increasing water-filled pore space (WFPS). Soil texture, total precipitation and water removal through soil drainage and evaporation is affected soil moisture which the most important factor controlling emissions of N_2O and NO (Hatano and Sawamoto 1997; Akiyama *et al.* 2000). In Simunjan (4095 mm yr^{-1}), the annual precipitation was higher than in Tunggal (1387 mm yr^{-1}) , however soil texture in Simunjan is sandy soil with high infiltration, drainage, and subsequent high soil aeration caused lower N_2O emission compared to sandy loam soil in Tunggal. It could be seen clearly as comparison in the Fig. 2.2 and Fig. 2.3 where the maximum precipitation at 50 mm, soil moisture tension showed as pF 0.5 and pF 2 in Tunggal and Simunjan, respectively. Thus, it explained that soil moisture content in Tunggal was higher than in Simunjan, since the lower value of soil moisture tension means the higher soil moisture content, and conversely, the higher the value the lower the moisture content (Tan 1996). Moreover, the WFPS was higher in Tunggal than in Simunjan (Table 2.1), thus the N_2O emission in Tunggal was higher compared to Simunjan. Soil water acts as transport medium for NO_3^- and NH_4^+, and control oxygen transport to soil and affect N gases out from the soil (McTaggart *et al.* 2002) and by that it controls whether process of nitrification or denitrification dominate inside the soil (Pilegaard 2013). Under soil with better aeration such as sandy soil, the aerobic process of nitrification was feasible to be the main source of N_2O emission, and therefore emission of NO may be more significant (Parton *et al.* 1988; Akiyama *et al.* 2000). After precipitation, the effect of soil texture in determining aeration and gas diffusion in soil was demonstrated important. Thus, soil water mainly regulating soil aeration condition as the significant factor for N_2O emissions in the tropical soil (Davidson 1991; Werner *et al.* 2007b), whereas by cause of complexity of interacting environmental control, it is difficult to capture the only one factor which the most predictive value affecting the N_2O emissions (Andersson *et al.* 2003).

In this study, patterns of N_2O emissions were affected by types of soil, precipitation and soil moisture. Considering types of soil, peat soil is known as organic soil has greater at least 12% organic contents on dry weight basis and more than 50 cm in depth (Inubushi 2015) compare to the mineral soil. The peat soil form where prolonged saturation with water results in a deficiency of oxygen, so that soil environment became anaerobic. In turn, decomposition of organic matter such as plant debris becomes slow, as the results promote the accumulation high amount of organic matter in the soil, sometime 50% in volume (Inubushi 2015). Peat soil such waterlogged areas are more generally present in wetlands and 10% of the global peatlands occurs in tropical lowlands (Hillel and Rosenzweig 2011). Soil organic matter is also a major source of N. Soils contain approximately 907 kg N in organic forms for each percent of organic matter. Decomposition of this portion of organic matter proceeds at a rather slow rate and releases about 22.4 kg N ha^{-1} yr^{-1} for each percent of organic matter. Then organic N that is present in soil organic matter and crop residues is converted to inorganic N through the process of mineralization (Lamb *et al.* 2014).

Freshly wetted soils have the high carbon and N availability that is linked to high denitrification rates (Peterjohn and Schlesinger 1991). The occurrence of rainfall events stimulates soil N mineralization (Jantalia *et al.* 2008). Tropical peat land could be a potential source of GHG emissions because peat soil contains large amounts of soil carbon and N (Ismunadji and Soepardi 1984; Melling *et al.* 2005). However, management practices via physical compaction could increase BD, resulting in higher capillary rise and high moisture content that could decrease the soil CO_2 flux (Melling *et al.* 2005). High N_2O fluxes in peat soils are further correlated significantly with denitrification activity where a high content of NO_3^-, NH_4^+ and WFPS are present in the soil (Ismunadji and Soepardi 1984). Large amounts of NH_4^+ and NO_3^- accumulate when organic matter in peat soil undergoes either aerobic or anaerobic decomposition (Ismunadji and Soepardi 1984). This could pose a great threat to the environment by emitting N_2O. Soil pH has a marked effect on the products of denitrification. Denitrification rates would be slower under the strong acid conditions in Tatau peat than under the slightly less acid conditions in the other two soils. This is commonly attributed to the sensitivity of N_2O reductase to proton activity, and it is also likely that all denitrifying enzymes are susceptible at low soil pH and produce N_2O from other intermediate products (Nägele and Conrad 1990).

In this study, coated fertilizer reduced N_2O emission in Tunggal sandy loam soil. However, coated fertilizer exhibited higher N_2O emission compared to conventional fertilizer in Simunjan sandy soil and Tatau peat soil. Delgado and Mosier (1996) observed similar results in which N_2O emissions from polyolefin-coated urea remained higher than non-coated urea through the growing season in a barley (*Hordeum vulgare* L.) field on sandy soil. Coated N fertilizer exhibits an intermediate rate of emissions that continue for a relatively long period. The effectiveness of coated fertilizers for N_2O emission mitigation depends on increases in the nitrification derived N_2O emissions after fertilizer application and on N substrate availability in Andosol and Fluvisol (Uchida *et al.* 2013). Application of conventional fertilizer often causes a sharp peak immediately after applying the fertilizer, while coated urea shows a broader peak (Akiyama *et al.* 2000). Additional results show that the effectiveness of coated fertilizer for N_2O mitigation was dependent on soil and land-use type, where coated fertilizer was significantly effective for imperfectly drained Gleysol grassland but not effective for well-drained Andosol upland fields (Akiyama *et al*. 2009).

Impact of fertilizer designed to reduce N_2O emission seems are inconsistent because of interact with weather factor which directly affect the process to lead to gaseous N losses and NO_3^- leaching and plant uptake factor which indirectly affect these N process in the soil (Ogle *et al.* 2014). Concerning with effectiveness of coated fertilizer to decrease N_2O emission on sandy loam soil than peat soil, it may be related with plant uptake by oil palm plantation which is affected by ages of oil palm. Coated fertilizer release N through coating and it has potential to reduce N_2O emission if the release of N from coated fertilizer is well synchronized with plant uptake (Shaviv 2001). However, when N release from coated fertilizer is not match with ability plant uptake, the efficiency coated fertilizer can be decline. It reported by Akhir *et al*. (2015) that N_2O emission influenced by ages of palm plantation. It found that N_2O emission was highest for oil palm aged < 5 years (immature) compared to mature palm in aged 5 – 20 and 21 – 30 years in Kempas, Malaysia. Furthermore, Basuki *et al.* (2014) explained that by increasing of oil palm age from > 3 to 16 years old, it decreasing gradually the total N content. It is indicated that by increasing the age of oil palm is related to greater N absorption by plant and consequently will decrease total N in the soil. Oil palm plantation as perennial crop, usually in mature palms are able to take complete nutrient for growth because of its complete root system compared to the young palm. As explained by Corley and Tinker (2003) stated that on the structure of oil palm roots in relation to nutrient acquisition, thus less of nutrient will be taken up by the roots when fertilizer applied at condition where the amount of roots at its minimum (Kheong *et al.* 2010). Therefore, maximum uptake of N fertilizer can occur at mature palms compared to immature palms. In mature palm has systematic and well established palm canopy cover and ground cover than can also reduce the nutrient leaching loss (Akhir *et al.* 2015).

In Tunggal sandy loam soil, oil palm age was 7 years old (mature) while in Tatau peat soil, age of oil palm was 4 years old (immature). It could be explained that possible reason coated fertilizer in Tunggal sandy loam soil was more effective because it have high plant uptake, so when the N release from coated fertilizer the root can be absorb N from the soil sufficiently due to complete root system. Hence, it will increase suitability of N for plant, and the amount of N_2O from nitrification will reduced. In contrast, in Tatau peat soil, one of the most difficult problems to counteract is the poor root anchorage provided by the soft peat (Dolmat *et al.* 1982). It may be difficult to reduce N_2O emission by coated fertilizer, when N uptake by plant occurs slower due to incomplete root system to absorb N from the soil inadequately. Consequently, on peat soil, denitrification is considered the main path of N_2O production with high decomposition of peat. High level of organic matter and application of N fertilizer on peat soil may induce higher N_2O emission (Bouwman 1996; Bremner 1997).

The emission factors are the highest for Tatau peat soil compared with Tunggal sandy loam and Simunjan sandy soil. These results are similar to the reported values in the Netherlands which indicated that the EF of synthetic fertilizer with nitrate was the highest in peat soil (3.68%), followed by clay soil (1.38%) and sandy soil (0.57%) (Kuikman *et al.* 2006). In well-drained Alluvial soil in Indonesia, the EF of urea and the controlled release factor (CRF-LP30) were 1.61% and 1.42%, respectively (Jumadi *et al.*

2008b). Therefore, these EF values are mostly dependent on management practices, fertilizer types, climates and soil types.

2.5.2 CO_2 fluxes correlated with soil types

Soil CO_2 flux is generally positively correlated with soil temperature (Lloyd and Taylor 1994; Davidson *et al*. 1998; Nagano *et al.* 2012) and the rates of soil CO_2 flux vary by ecosystem (Raich and Schlesinger 1992; Melling *et al.* 2005). In this study, the soil CO_2 fluxes were not directly influenced by soil temperature. In the Tatau peat soil, as the soil temperature decreased, the soil CO_2 fluxes tended to increase. This may be confounded with the increase in oil palm growth, where higher root biomass would result in higher root respiration. The root biomass could have also stimulated the soil microbial activity, which enhanced the soil CO_2 fluxes. In the other two mineral soils, the CO_2 fluxes tended to be higher in the Simunjan sandy soil than in the Tunggal sandy loam soil. In the Tatau peat soil, CO_2 fluxes were the highest among three soils examined which may be due to higher soil carbon content. The relationship between quantity of soil carbon, soil CO_2 flux and litter respiration remains a serious concern (Gu *et al.* 2004). The rate of CO_2 transmission from soils to the atmosphere is determined by microbial respiration, root respiration and bulk soil respiration and is predominately regulated by soil microorganisms found within the soil organic matter (Raich and Schlesinger 1992).

In this study the N_2O and CO_2 correlations revealed the linear regression varied depending on the study site. Linear regression between N_2O and CO_2 found higher in Tatau peat soil than in Tunggal sandy loam and in Simunjan sandy soil (Fig. 2.5). The variation may reflect the differences in soil carbon and nitrogen composition and the effect on climate and soil environmental conditions (Xing *et al.* 2002). Garcia-Montiel *et al.* (2002) explained the positive correlations between N_2O and CO_2 as the result of O_2 availability in soil microsites. A higher soil CO_2 emission rate indicates greater decomposition, which consumes oxygen, and creates the anaerobic conditions that are favourable for N_2O production via denitrification. The linear relationship between N_2O and CO_2 fluxes was also found across several types of ecosystems, such as rice paddy, dry cropland, bogs and fens, and subtropical and tropical moist forest (Xu *et al.* 2008).

2.6 Conclusion

The effect of soil types on N_2O and CO_2 fluxes in the studied tropical oil palm plantation was highly significant, but no consistent tendency was observed using different N fertilizers. N_2O and CO_2 fluxes showed high variation with soil types, N fertilizer and seasons. N_2O fluxes were the highest in the Tatau peat soil, followed by the Tunggal sandy loam soil and the Simunjan sandy soil, respectively. There was a significantly positive linear correlation between fluxes of N_2O and CO_2. Applications of fertilizer have to be considered with the suitability of the soil type to mitigate the gas emission to the atmosphere. Further detailed study is needed to assess a more accurate interpretation of the mechanism of N_2O and CO_2 fluxes in oil palm plantations.

Table 2.1 Descriptions and physicochemical characteristics of soils at the oil palm plantation study sites

Description	Study Sites		
	Tunggal	Simunjan	Tatau
Soil type	Ultisols	Ultisols	Histosols (Peat)
Texture	Sandy loam (62% sand, 5% clay, 33% silt)	Sandy (97% sand, 0.03% clay, 2.97% silt)	-
Total Area (ha)	14,000	7,900	9,000
Studied Area (ha)	93.6	4.4	3.52
Planting Density (palm ha^{-1})	135	136	150
Age of palm trees	7 yr. (mature)	9 yr. (mature)	4 yr. (immature)
Pre-oil palm vegetation	Rubber plantation	Primary and secondary forest	Acacia garden
NO_3^- (mg N kg^{-1}ds)	16.2±7.61	1.41±0.93	77.8±18.6
NH_4^+ (mg N kg^{-1}ds)	31.9±8.05	16.2±12.1	122.8±22.1
Total N (g kg^{-1}ds)	2.17±0.31	1.70±0.26	17.2±3.90
Total C (g kg^{-1}ds)	23.4±4.71	18.5±0.56	467±71.0
pH (KCl)	4.67±0.10	4.77±0.06	3.34±0.08
Bulk Density (g cm^{-3})	1.1±0.1	1.5±0.0	0.2±0.0
WFPS (%)	75.9±3.0	74.4±1.2	83.5±4.0

yr., year, means ± standard deviation, n = 3. nitrate (NO_3^-); ammonium (NH_4^+); total nitrogen (Total N); total carbon (Total C); bulk density (BD); water-filled pore space (WFPS). Rubber (*Hevea brasiliensis*); Acacia (*Acacia mangium*). Soil sampling was conducted in August 2011, before fertilizer application on fine days with no rain during the dry season.

Table 2.2 Nitrous oxide (N_2O) fluxes for the three study sites during wet and dry seasons

Study sites	Treatments	N_2O flux (μg N m^{-2} h^{-1})	
		Wet season	Dry season
Tunggal	B	33.7±49.6	6.27±0.44
	B2	27.4±20.3	19.1±4.52
	C	89.7±14.1	17.3±1.45
	M	28.2±36.0	8.30±5.87
Simunjan	B	3.81±1.42	2.40±4.79
	B2	0.80±3.65	1.63±1.12
	C	1.60±1.57	3.20±2.51
	M	2.18±2.73	5.34±7.03
Tatau	B	131±77.2	66.1±49.9
	B2	523±441	93.7±80.6
	C	249±77.3	185±15.5
	M	272±151	606±421
ANOVA	*df*	*F* value	*p* value
Sites	2	28.925	0.000
Treatments	3	2.282	0.091
Seasons	1	0.876	0.354
Sites x treatments	6	2.449	0.038
Sites x seasons	2	0.303	0.740
Treatments x seasons	3	2.755	0.053
Sites x treatments x seasons	6	2.811	0.020

Data are presented as the means ± standard deviation (n = 3). B, no fertilizer with no tillage; B2, no fertilizer with tillage; C, conventional fertilizer; M, coated fertilizer; N, nitrogen; ANOVA, analysis of variance; df, degrees of freedom. Wet season: from October to March; dry season: from April to September.

Table 2.3 Cumulative nitrous oxide (N_2O) fluxes for the three study sites

Study Sites	Cumulative N_2O fluxes (kg N ha^{-1} $period^{-1}$)			
	B	B2	C	M
Tunggal	0.59±0.11	2.14±0.64	4.09±0.84	1.99±2.16
Simunjan	0.25±0.14	0.11±0.08	0.18±0.18	0.42±0.30
Tatau	11.1±7.02	22.5±18.9	24.2±6.58	42.7±24.6
ANOVA	*df*	*F* value	*p* value	
Sites	2	25.937	0.000	
Treatments	3	2.115	0.125	
Sites x treatments	6	1.881	0.126	

Data are presented as the means ± standard deviation (n = 3). B, no fertilizer with no tillage; B2, no fertilizer with tillage; C, conventional fertilizer; M, coated fertilizer; N, nitrogen; ANOVA, analysis of variance; df, degrees of freedom.

Table 2.4 Emission factors (EF) calculated for the three study Sites

Study Sites	EF (%)	
	C	M
Tunggal	2.29±0.33	-0.33±0.35
Simunjan	-0.26±0.08	0.49±0.40
Tatau	19.13±2.46	43.8±16.7

ANOVA	*df*	*F* value	*p* value
Sites	2	40.012	0.000
Treatments	1	5.415	0.038
Sites x treatments	2	6.931	0.010

Data are presented as the means ± standard deviation (n = 3). C, conventional fertilizer; M, coated fertilizer; ANOVA, analysis of variance; df, degrees of freedom.

Table 2.5 Pearson correlation of nitrous oxide (N_2O) emission factors (EF) between the conventional fertilizer and the coated fertilizer among soil parameters for the three study sites (n = 9)

	N_2O EF (%)	
Soil Parameters	C	M
NO_3^-	0.966^{**}	0.794^{*}
NH_4^+	0.960^{**}	0.832^{**}
Total N	0.951^{**}	0.850^{**}
Total C	0.954^{**}	0.939^{**}
pH	-0.979^{**}	-0.943^{**}
BD	-0.977^{**}	-0.891^{**}
WFPS	0.834^{**}	0.729^{*}

EF, emission factors; C, conventional fertilizer; M, coated fertilizer; ** significant at 0.001; * significant at 0.05. nitrate (NO_3^-); ammonium (NH_4^+); total nitrogen (Total N); total carbon (Total C); bulk density (BD); water-filled pore space (WFPS).

Table 2.6 Carbon dioxide (CO_2) fluxes for the three study sites during the wet and dry seasons

Study sites	Treatments	CO_2 flux (mg C m^{-2} h^{-1})	
		Wet season	Dry season
Tunggal	B	45.5±0.93	56.4±2.78
	B2	50.6±11.3	61.3±6.05
	C	49.0±18.9	95.4±10.9
	M	56.8±15.3	96.5±15.1
Simunjan	B	72.1±10.9	104±8.55
	B2	71.1±3.66	134±34.5
	C	101±14.0	126±10.2
	M	114±7.93	105±46.5
Tatau	B	89.8±43.5	92.7±23.1
	B2	223±93.2	129±31.7
	C	158±45.0	153±75.7
	M	153±49.9	208±107
ANOVA	*df*	*F* value	*p* value
Sites	2	34.525	0.000
Treatments	3	4.287	0.059
Seasons	1	1.576	0.215
Sites x treatments	6	1.608	0.165
Sites x seasons	2	2.179	0.124
Treatments x seasons	3	1.051	0.379
Sites x treatments x seasons	6	1.450	0.216

Data are presented as the means ± standard deviation (n = 3). B, no fertilizer with no tillage; B2, no fertilizer with tillage; C, conventional fertilizer; M, coated fertilizer; ANOVA, analysis of variance; df, degrees of freedom. Wet season: from October to March; dry season: from April to September.

Table 2.7 Cumulative carbon dioxide (CO_2) fluxes for the three study sites

Study sites	Cumulative CO_2 fluxes (kg C ha^{-1} period^{-1})			
	B	B2	C	M
Tunggal	5302±420	5655±634	6888±112	7971±172
Simunjan	9002±467	7638±139	10803±165	11431±371
Tatau	8797±364	13588±407	15328±608	16950±690
ANOVA	*df*	*F* value	*p* value	
Sites	2	13.62	0.000	
Treatments	3	3.094	0.064	
Sites x treatments	6	0.657	0.684	

Data are presented as the means ± standard deviation (n = 3). B, no fertilizer with no tillage; B2, no fertilizer with tillage; C, conventional fertilizer; M, coated fertilizer; ANOVA, analysis of variance; df, degrees of freedom.

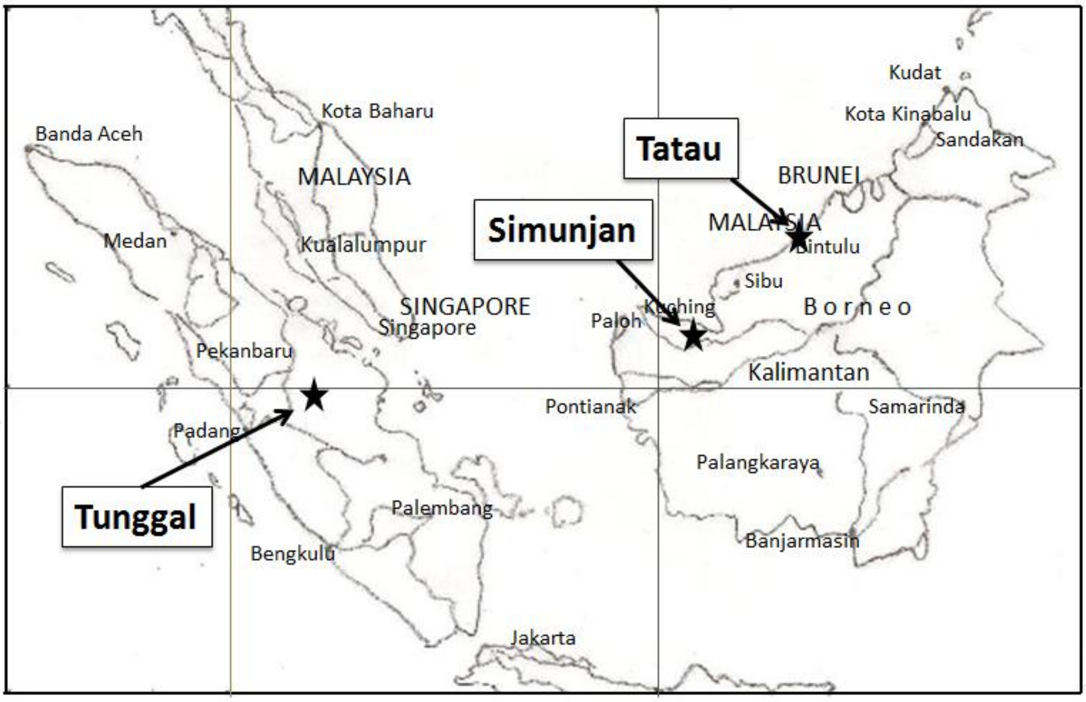


Figure 2.1 Map of study sites in Indonesia and Malaysia.

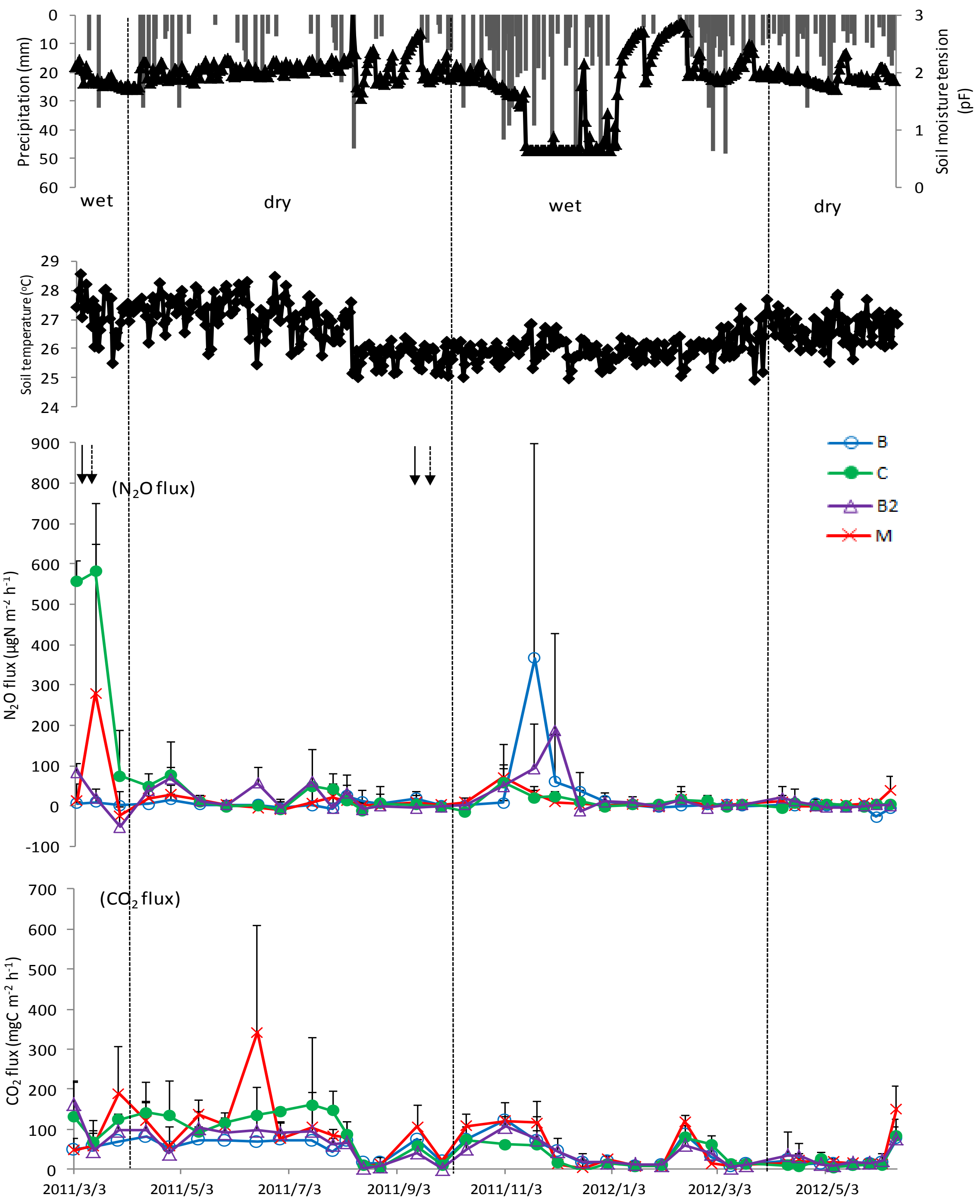


Figure 2.2 Precipitation, soil moisture tension, soil temperature, nitrous oxide (N_2O) flux and carbon dioxide (CO_2) flux in Tunggal sandy loam soil. Vertical bars indicate ± standard deviation. Treatment B: no nitrogen (N) fertilizer and no tillage; C: conventional fertilizer; B2: no N fertilizer with tillage; M: coated fertilizer. Solid arrows and dashed arrows indicate conventional and coated fertilization timing, respectively. Vertical dashed lines indicate transition period for dry and wet seasons.

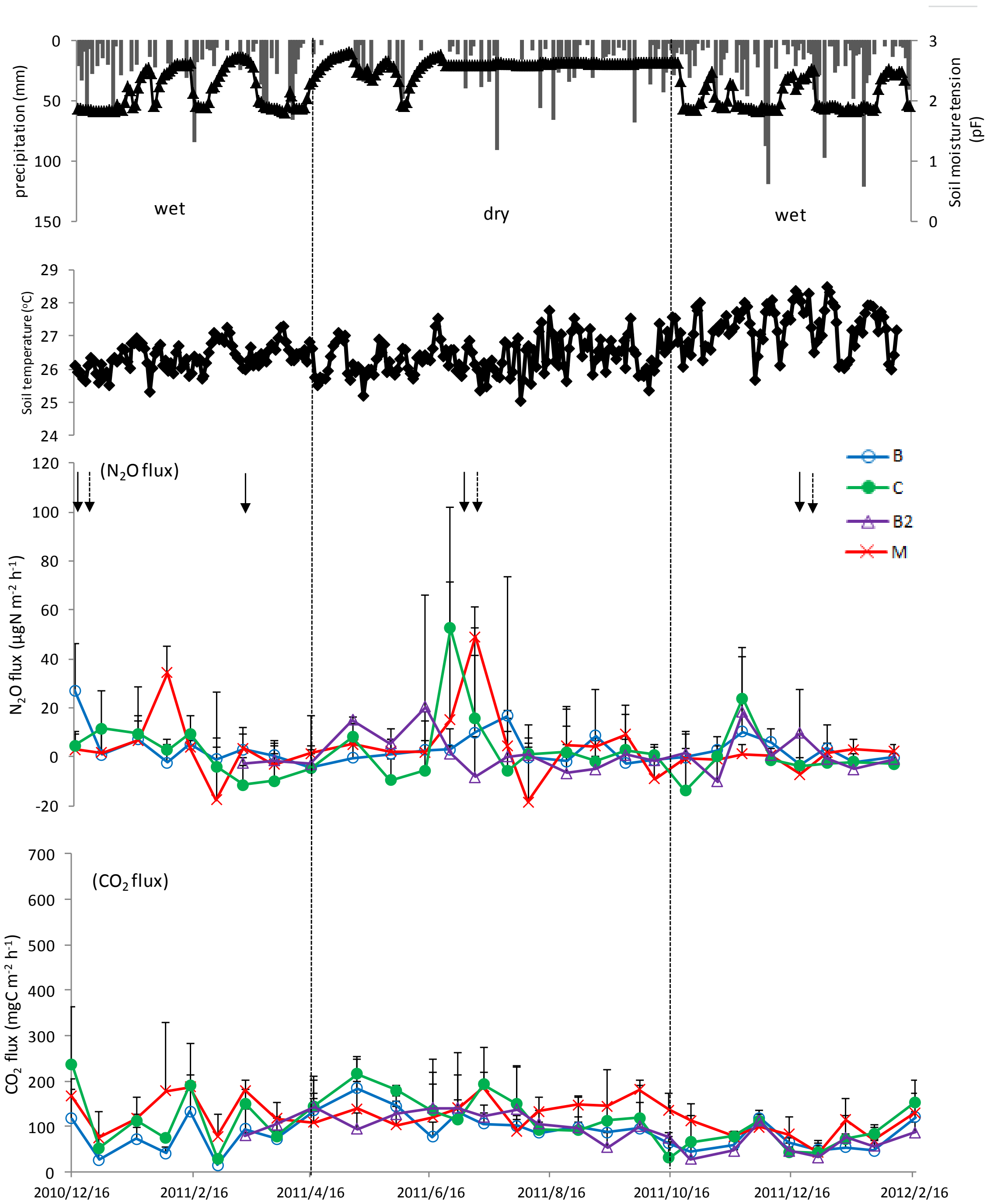


Figure 2.3 Precipitation, soil moisture tension, soil temperature, N_2O flux, and CO_2 flux, in Simunjan sandy soil. See details for other remarks in Fig. 2.2.

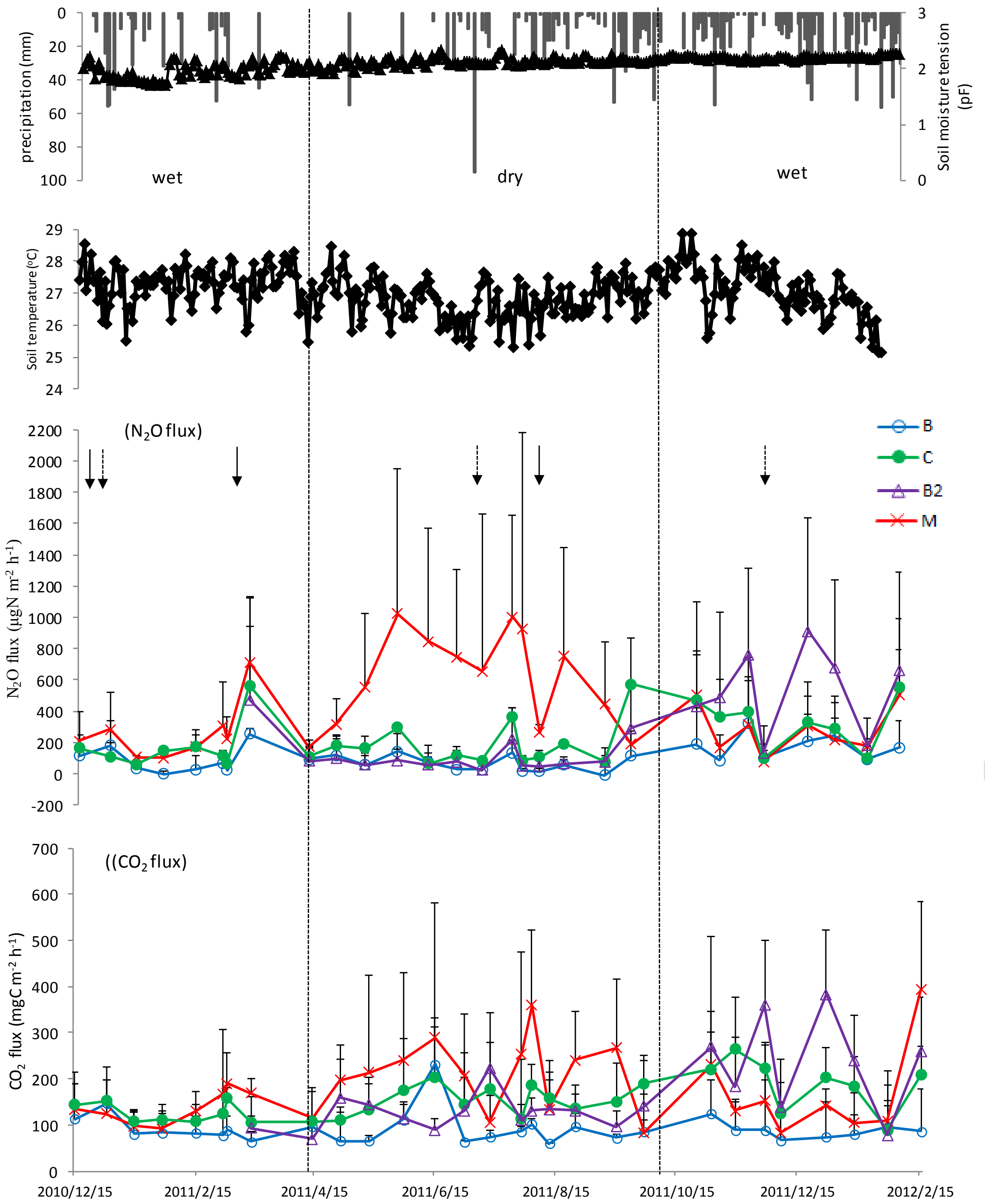
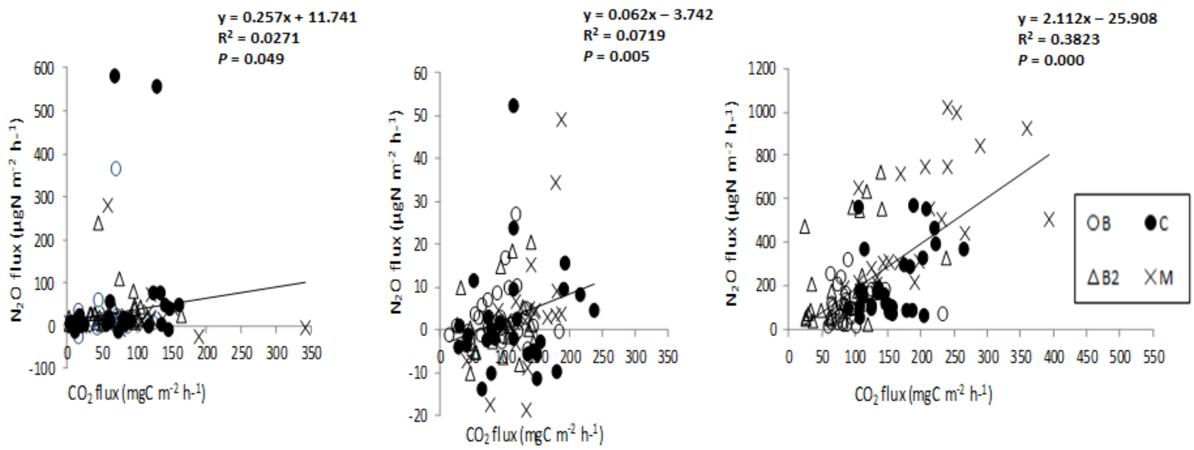


Figure 2.4 Precipitation, soil moisture tension, soil temperature, N_2O flux, and CO_2 flux, in Tatau peat soil. See details for other remarks in Fig. 2.2.



(a) Tunggal (b) Simunjan (c) Tatau

Figure 2.5 Linear relationship between N_2O and CO_2 flux in (a) Tunggal, (b) Simunjan, and (c) Tatau. Abbreviations of symbols can be found in the materials and methods section.

Chapter 3

Effect of topography on N_2O and CO_2 emissions and dissolved N_2O in oil palm plantation in Riau, Indonesia

3.1 Abstract

The oil palm plantations have been expanding into the different slope positions. However the interactions of soil properties and topography influencing greenhouse gas fluxes are still poorly understood. Topography affects the movement of surface and subsurface water and causes the variability of soil processes, which makes the accurate estimation of greenhouse gas fluxes more difficult. This study aimed to assess N_2O and CO_2 emissions, measured by closed chamber method in upper, middle, and lower slope positions for a whole year from June 2012 to May 2013 in Tunggal sandy loam soil, Indonesia and to assess the dissolved N_2O concentration as source of indirect emission from oil palm plantation to the atmosphere, measured by headspace method in puddle, drains, and wells. N_2O and CO_2 fluxes showed variability with seasons and slope positions. Cumulative N_2O fluxes were significantly higher in the lower position than upper and middle position, while cumulative CO_2 fluxes showed no significant difference among the slope positions. Dissolved N_2O concentrations varied by water

sources and sampling time, sometimes supersaturated than ambient equilibrated concentration. These results show that topography even in a short slope affected the spatial variability of N_2O and CO_2 emission, which may need to be taken into account in field measurements and estimating the whole emissions of these gases including the indirect emissions.

Key words: N_2O flux, CO_2 flux, dissolved N_2O, indirect emission, topography

3.2 Introduction

Nitrous oxide (N_2O) is potent greenhouse gases with much greater global warming potential than carbon dioxide (CO_2). N_2O emissions have been shown to vary across agricultural landscapes in response to variations in several factors such as topography, soil, crop types and managements (Izaurralde *et al.* 2004; Vilain *et al.* 2010). Topography is well documented to cause variability of environmental factors such soil temperature and moisture, and other properties have to be identified in relation to the soil carbon (C) and nitrogen (N) cycling processes (Luizao *et al.* 2004). Soil factors related to topography may also influence nitrifier and denitrifier's communities with respect to N_2O turnover and interact with soil respiration (Zhu *et al.* 2013; Philippot *et al.* 2009; Banerjee and Siciliano 2012). Soil respiration is one of the main components of ecosystem respiration (Granier *et al.* 2000; Janssens *et al.* 2001). CO_2 release from soil, commonly referred as soil respiration, and even small changes in soil respiration may strongly affect soil carbon sequestration in long-term (Raich and Schlesinger 1992). Due to increased global demand of palm oil, plantation area of oil palm has been expanding to the hilly area. Annual exchange of CO_2 from tropical ecosystem has also potential significance for the global carbon cycle and climatic change (Sorensen 1993).

In general, it has been observed that N_2O emissions were higher in lower slope position than in upper slope positions because the lower slope position have greater soil moisture, plant biomass, and soil C content (Hook and Burke 2000). Effects of soil temperature and soil water content on CO_2 emission was observed in managed forests in Canada (Peng and Thomas 2006). Tropical rainforest showed that the temporal variability of soil CO_2 efflux was depended mainly on soil water content (Kosugi *et al.* 2007).

Indirect N_2O emissions are recognized as a quantitatively significant component of the total N_2O emission budget from agricultural activities (Reay *et al*. 2009). The proportion of leached N that is emitted as N_2O is termed an emission factor (EF), and for aquatic ecosystems, this is referred to as EF5. The EF5 consists of emission factors for groundwater and surface drainage (EF5-g), rivers (EF5-r), and estuaries (EF5-e) (IPCC 2006). EF5-g is derived from the ratio of dissolved N_2O to NO_3^- concentrations (Mosier *et al.* 1998). It is thought that N_2O emissions through groundwater comprise a significant fraction of total agricultural N_2O emissions and default value of EF5-g (N_2O-N / NO_3^--N) is 0.0025 (IPCC 2006).

In Indonesia, N_2O and CO_2 emission from oil palm plantation have reported as affected by converted land (Dewi *et al*. 2009), linked to fertilizer use (Murdiyarso *et al.* 2002), related to land use change (Hadi *et al.* 2012), and affected by the soil types (Sakata *et al.* 2015). However, the interactions of soil properties and topography influencing soil N_2O and CO_2 emissions, and dissolved N_2O are still poorly understood. Oil palm plantation is located in the different slope variation. Therefore it is necessary to conduct study to assess the N_2O and CO_2 emissions as affected by topography and to identify the controlling factors of spatial variations in N_2O and CO_2 emissions at the landscape scale, and to assess the dissolved N_2O concentration as source of indirect emission.

3.3 Materials and methods

3.3.1 Site descriptions

The study site was located in Tunggal Plantation, 200 km southeast of Pekanbaru City, Airmolek District, Riau Province, Indonesia (S00°20.731′ E102°17.617′) on sandy loam soil classified as Ultisols (the United States Department of Agriculture (USDA) soil taxonomy) (Fig.3.1). Geographical feature of Tunggal Plantation is categorized as hilly slope area, with annual rainfall and mean temperature was 1387 mm and 28°C, respectively. Oil palms (*Elaeis guineensis* Jacq.) in study area were planted at a density of 135 palms per hectare. Total study area was 93.6 ha and the age of plantation was 7 years (mature palm). Annual rates fertilizer application was 151 kg N ha^{-1} as NPK (16-4-25) as split applications twice with equal amounts in June and September. The precipitation data were collected by oil palm plantation staff members from rain gauges located within the oil palm plantations.

3.3.2 Physicochemical analysis of the soil samples

Along the sloping from 1.3 to 2.2% (Fig. 3.1), undisturbed soil core with three replicates and composite soil samples were collected at 0-10 cm depth at upper, middle, and lower slope position. The soil sample was collected three times, on 12 June 2012, 2

October 2012, and 31 January 2013. The soil samples were analysed for their physical and chemical properties. Prior to analysis, the soil samples were maintained at 4°C. The undisturbed soil cores were used for soil volume measurements using a three-phase meter (DIK-1130, Daiki Rika Kogyo Co. Ltd). The core samples were weighed and then oven dried at 105°C for 48 h. After drying, the core samples were reweighed to calculate soil moisture content, bulk density (BD), and water-filled pore space (WFPS). Soil particle size distribution was determined by the Bouyoucos hydrometer method (Kroetsch and Wang 2008)**.** The soil pH was measured by pH meter (D-52, Horiba Co., Ltd) with a glass electrode. Part of the soil samples were air-dried and passed through a 0.5 mm sieve, and the sieved soil was used to determine total carbon and nitrogen contents using a Carbon and Nitrogen Analyzer (CN corder; MT-700 Yanaco Analytical Industry Co., Ltd). The inorganic N contents of NH_4^+ and NO_3^- were determined by sieving fresh soil through a 2 mm sieve, extracting it in 1 M KCl of 1:2.5 ratio, and using the nitroprusside method (Anderson and Ingram 1989) and hydrazine reduction method (Hayashi *et al*. 1997), respectively.

3.3.3 Measurement of N_2O and CO_2 fluxes

Measurement of N_2O and CO_2 fluxes was conducted at 2-weeks interval from June 2012 to May 2013 at each slope positions. Gas sampling was consistently conducted by closed chamber method at mid-morning with 3 replications, based on previous study on oil palm plantation (Sakata *et al.* 2015). N_2O and CO_2 fluxes were measured by a gas chromatograph (GC-14B, Shimadzu, Japan) equipped with an electron capture detector and thermal conductivity detector, respectively.

3.3.4 Chemical analysis for the water samples and measurement of dissolved N_2O concentrations

Water samples were collected at puddle in lower slope, drains and wells (Fig. 3.1). It was conducted 3 times, on 2 June 2012, 12 October 2012, and 31 January 2013. Each water samples was collected in 50 ml plastic bottle for NH_4^+ and NO_3^- concentration measurement, and 22 ml vacuum vial for dissolved N_2O concentration measurement, respectively, and then brought back to the laboratory. The water samples were stored in a refrigerator and analysed within one week. NH_4^+ and NO_3^- were determined by filtering the water samples through filter paper (Advantec 131, 150 mm, Toyo Roshi Kaisha Ltd., Japan) and analysed using the nitroprusside method (Anderson and Ingram 1989) and hydrazine reduction method (Hayashi *et al*. 1997), respectively. For measurement of dissolved N_2O concentrations, 5 ml of each water samples was transferred into another vacuum vial, and filling with 17 ml helium gas, and shake properly. The N_2O gas in the headspace was measured by gas chromatography with 3 replicates. Dissolved N_2O concentration was calculated based on Sawamoto *et al.* (2002).

3.3.5 Statistical analysis

Statistical analyses were conducted using IBM SPSS Statistics 21. Means of N_2O and CO_2 fluxes for each slope positions during wet and dry seasons were analysed using a two-way ANOVA test. While, the significance of the cumulative N_2O and CO_2 fluxes for each slope positions were analysed using a one-way ANOVA test. Correlations between seasonal mean gas emissions (dry season in 2012, wet and dry seasons in 2013) and soil physiochemical properties among the slope positions in June and October 2012 and January 2013 were analysed using Pearson's correlation, respectively. Statistical considerations were based on $p < 0.05$ significance level. Correlation between NO_3^- and dissolved N_2O concentration were analysed using simple linear regression.

3.4 Results

3.4.1 Physicochemical soil properties by slope positions

Physicochemical properties of soil varied widely by slope positions (Table 3.1). NO_3^-, NH_4^+, and WFPS showed higher tendency in lower slope than in upper and middle slope positions, although other soil parameter such as total C, total N contents, pH, and bulk density did not show the same tendency.

3.4.2 Soil N_2O emission

N_2O fluxes in the upper, middle, and lower slope positions varied by seasonal (Fig. 3.2). N_2O fluxes were in the range from 0.34 to 36.3, -4.28 to 34.9 and 1.59 to 61.2 μg N m^{-2} h^{-1} in the upper, middle, and lower slope positions, respectively. High peak of N_2O fluxes (31.6 – 59.4 μg N m^{-2} h^{-1}) were observed after second fertilization followed with precipitation, and again reached high peak of N_2O (32.6 – 61.2 μg N m^{-2} h^{-1}) during wet season with high precipitation. The highest peak of N_2O was observed in the lower slope position. The temperature showed no correlation with variation of N_2O flux in different slope positions. During the study period, N_2O fluxes were higher in wet season than in dry season (Table 3.2). During the wet season, N_2O fluxes were highest in the lower slope than upper and middle slope. During the dry season, effect of slope positions was no observed in N_2O fluxes. Two-way ANOVA analysis showed significant interaction between seasons and slope positions (*p* = 0.027) (Table 3.2). The cumulative N_2O fluxes were 460, 560, and 697 g N ha^{-1} y^{-1} in the upper, middle, and lower slope positions, respectively. Cumulative N_2O fluxes were significantly higher in the lower slope, while upper and middle slope positions showed no significant difference (Fig. 3.3). Effect of slope positions related with cumulative N_2O emissions showed positive correlation with the NO_3^- and WFPS (Table 3.4).

3.4.3 Soil CO_2 emission

CO_2 fluxes in the upper, middle, and lower slope positions varied seasonally (Fig. 3.2). CO_2 fluxes were ranged from 15.2 to 166, 10.1 to 128, and 0.72 to 187 mg C m^{-2} h^{-1} in the upper, middle, and lower slope positions, respectively. The precipitation and temperature showed no correlation with variation of CO_2 flux in different slope positions.

During the study period, CO_2 fluxes were higher in dry season than in wet season. CO_2 fluxes were significantly different among the seasons ($p < 0.001$). However, effect of slope positions on CO_2 fluxes showed no significant difference in both wet and dry seasons (Table 3.3). The cumulative CO_2 fluxes were about 6270, 7370, and 7600 kg C ha^{-1} y^{-1} in the upper, middle, and lower slope positions, respectively. Cumulative CO_2 fluxes were not significantly different among the slope positions (Fig. 3.3). Cumulative CO_2 emissions showed significantly positive correlation with the WFPS (Table 3.4).

3.4.4 NH_4^+, NO_3^-, pH, dissolved N_2O and CO_2 concentrations in water samples and emission factors

NH_4^+, NO_3^-, pH and dissolved N_2O and CO_2 concentrations varied among the source of water. NH_4^+ concentrations were lower than 1 mg N L^{-1}, except in the puddle sample taken in June. NO_3^- concentrations were also lower than 1 mg N L^{-1}, except in the puddle samples, increasing from June 2012 to January 2013 (Fig. 3.4). The pH value in all water samples were range from 5.8 to 6.7 during the measurement. Higher pH value showed in all samples taken in June 2012 and pH value slightly decreased in October 2012 and January 2013 (Fig. 3.5). Dissolved CO_2 concentration showed the opposite with pH value. Dissolved CO_2 concentrations range from 0.004 to 0.248 mg L^{-1}. High concentration of dissolved CO_2 from all water samples observed in January 2013 during the wet season (Fig. 3.5).

Dissolved N_2O was the highest in the drain 1 in October 2012, and the lowest in puddle in June 2012. These concentrations were supersaturated (0.45–39.1 times higher) than ambient equilibrated concentration as leading possibility to be source of indirect emission. NO_3^- concentration in the well 2 (394 cm depth) was higher than in well 1 (515 cm depth). Significant relationship between the N_2O-N and NO_3^--N showed significant in drains and puddle, but not significant in wells (Fig. 3.6). Value of ratio N_2O-N to NO_3^--N as emission factor for groundwater (EF5-g) for puddle was below the IPCC (2006) default EF5-g value, 0.0025, while the EF5-g for drain was above the IPCC value. EF5-g in this study varied among source of water and in the range from 0.0007 to 0.0453.

3.5 Discussion

3.5.1 N_2O and CO_2 fluxes correlated with soil physicochemical along the slope positions

Differences in soil moisture levels between slope positions are typically related with redistribution of water by runoff, and runoff may occur under high precipitation during wet season (Vilain *et al*. 2010). This study showed high WFPS in lower than upper and middle slope positions (Table 3.1). In several Canadian agricultural regions, soil water content has been found to be the main driver of N_2O fluxes at the landscape scale (Corre *et al*. 1999; Izaurralde *et al*. 2004). Since soil water content was relatively high, WFPS values reached to favor for denitrification and N_2O production (Linn and Doran 1984).

In this study, high N_2O flux was observed after the second time of fertilization followed by precipitation in dry season, and then showed high peak in the end of wet season (Fig. 3.2). As observed by Corre *et al.* (1999), a particular precipitation level occurring immediately after fertilization showed much higher N_2O fluxes. Average N_2O emission was 1.92 to 2.96 times higher during wet season than dry season (Table 3.2). Result of this study was similar to the observation in toposequences in Alberta, Canada, where the N_2O emissions during wet season were higher than dry season (Izaurralde *et al.* 2004). Several studies showed that higher N_2O was emitted in a normal or wetter year with greater precipitation than in a dry year (Laville *et al*. 2011; Parkin and Kaspar 2006). In this study, during wet season, the emitted N_2O in the lower position was 1.31 to 1.63 times more than those in the middle and upper slope positions, respectively (Table 3.2). This result indicated that the effect of slope position associated with soil moisture on N_2O emission is comparable to that of season.

The N_2O emissions were found to be significantly correlated positively with NO_3^- concentration (Table 3.4). These results indicated that the soils might have a stronger denitrification process in the lower part than in the upper part. Qian and Schoenau (1995) reported greater NO_3^- release from the lower slope soils of higher organic matter compared to the upper slope soils. More NO_3^- concentration in the lower part also mean that there was more NO_3^- source therein to fuel the denitrifiers and thereby promote denitrification in combination with higher soil water content (lower oxygen concentration) (Fang *et al.* 2009; Vilain *et al.* 2010), and therefore it found higher N_2O flux in lower slope than in the middle and upper slope positions. The NO_3^- loss from the upper part of the slope could be attributed to crop uptake, low organic matter mineralization, and/or NO_3^- loss due to leaching and denitrification. Although crop uptake, leaching, and denitrification would have also occurred on the lower slope, mineralization and N transport with runoff from upslope areas might have been sufficiently high to compensate for the losses (Priyashantha *et al.* 2007).

Mineralization is the conversion of an element from an organic form to an inorganic as a result of microbial decomposition. Through mineralization, organic form of N in soil is converted to NH_4^+. Soon and Malhi (2005) observed that mineralization was less at the upper than at the lower slope position which mainly influenced by low organic matter content and soil water availability. Topography is a main factor of N mineralization, nitrification and denitrification processes through its control on factors such as soil moisture, soil temperature and nutrient availability (Stewart *et al*. 2014).

The influence of topography on cumulative CO_2 flux along the slope was not significant in this study (Fig. 3.3). The study result was similar to those observed in tea plantation on Typic Hapludalfs, in Malino, South Sulawesi province, Indonesia (Jumadi *et al.* 2008a). Even the cumulative CO_2 flux showed no significance, it tended to be higher in lower and middle slopes rather than in the upper slope. This may be attributed to soil erosion, therefore in the lowered parts, plant growth, belowground C allocation, and soil C content increase, providing more C substrate for the activities and respiration of plant roots and soil microorganisms (Liu *et al*. 2007). Significant effects of topography on CO_2 flux were observed 6% higher in the lower than upper slope during growing season in semiarid grassland, northern China (Xu and Wan 2008). In this study, means of CO_2 fluxes were higher in dry season than in wet season (Table 3.3). Variations in soil air components exist with different seasons. High soil moisture as in the wet season may induce low oxygen and high CO_2 level in the soil air. Because soils are normally drier in the dry season, opportunity for gaseous exchange is greater during this period. However, there are some exemptions to this rule. Since high temperature in the dry season may also encourage rapid microbiological release of CO_2, a given soil containing easily decomposable organic matter may have higher CO_2 level than in the wet reason (Yerima and Ranst 2005).

In perennial crops, variation in soil properties over the topography position showed that concentration of soil chemical properties was higher on lower slope that on eroded upper slope (Steinwald *et al.*1996). Apart from soil properties, as function of slope position also has been revealed vary on crop yields (Mahli *et al.* 1993). Due to increasing nutrient accumulation toward the lower slope as effect of nutrient movement to the bottom part (Tan *et al.* 2014), therefore at lower slope positions allocated greatest potential yield (Nolan *et al.* 1995).

In Indonesia, some of the oil palm plantations are located in hilly area. Balasundram *et al. (2006*) observed that the highest yield occurring at the lower slope and the lowest yield from the upper slope in oil palm plantation, in South Sumatera, Indonesia. It is clearly explained that topography affected soil fertility and oil palm yield with 4-12% degree of slope. In Addition, in Malaysia estimation of potential yield from different region which located in sloping area reported that degree of steep influences yield of oil palm. In wet region on 7 years of harvesting showed the fresh fruit bunch (FFB) yield as 31-32, 29-30, 24-25 ton ha^{-1} at undulating area (0-12%), rolling area (12-24%), and hilly or steep area (24-50%), respectively. While in dry region, it showed FFB yield as 20-22, 18-19, 16-17 ton ha^{-1} at undulating area (0-12%), rolling area (12-24%), and hilly or steep area (24-50%), respectively (Paramananthan 2013). Generally, the yield trend is attributable to topographic difference. It can be explain that topography affect the movement of water nutrient which is affected by precipitation pattern of plantation areas.

Fertilizer management on sloping or hilly area which used for oil palm plantation is very essential to be taken. It is related to maintain fertility of the soil and to minimize soil erosion and nutrient loss from the area of plantation. Decreasing of nutrients through leaching and runoff reduces both crop productivity and economic gains. It recommended that frequence of fertilizer application at low rates is preferred on sloping land where the risk of nutrient losses through runoff or drainage is great (Goh and Chew 1995). The optimal frequency of fertilizer application depends on crop requirements, tree age, ground conditions, type of fertilizer available and precipitation. To diminish soil erosion and to sustain the soil moisture, frond heap as a plant residues added to ground surface of oil palm area (Redshaw 2003) and the threshed fronds are normally placed between palm trees as sources of nutrients (Kee and Chew 1997) as well. Besides as erosion control, frond heaps can supply organic matter and nutrients to soil through decomposition and influence nutrient cycling between the plant and soil systems (Yusuyin *et al.* 2015). On the steep areas where are prone to soil erosion, comprise the buffer strip, platform or terrace on each different of slope positions to improve the fertilizer use efficiency and yield harvesting is suggested (Gillbank 2003).

3.5.2 Dissolved N_2O concentration and emission factor for ground water

In this study, change of dissolved N_2O concentrations in the puddle may indicate that the relative importance of N_2O formation by nitrification of NH_4^+ (Fig. 3.4). It demonstrated that seasonal changes of NH_4^+ and NO_3^- in the puddle were different. NH_4^+ sharply decreased from 2.08 to 0.47 mg N L^{-1} from June to October and then stayed constant, while NO_3^- increased constantly from 0.38 to 5.62 mg N L^{-1} in the experimental period. As NH_4^+ was nitrified to NO_3^- then transported entering to groundwater, thus potentially contributing NO_3^- to N_2O production (Hinshaw and Dahlgren 2013). Aquatic ecosystems can be a significant source of N_2O emissions by both nitrification and denitrification to be considered as the two main processes producing N_2O. Nitrification, an aerobic microbial process, oxidizes NH_4^+ to NO_3^-, in which N_2O is formed as a byproduct (Knowles 1982). Denitrification is an anaerobic respiration process that reduces NO_3^- to dinitrogen gas (N_2), with N_2O as the intermediate gas product (Seitzinger *et al.* 2000). As a result of NO_3^- consumption in denitrifying in the aquifers, NO_3^- concentration in deeper groundwater is lower (Weymann *et al.* 2008). In this study, it was observed that NO_3^- concentration in the well 2 (in 394 cm depth) was higher than in well 1 (in 515 cm depth), while the dissolved N_2O tended to be higher in the well 1 than in the well 2 in October when decreasing NH_4^+ concentration became stable. The other possibility to explain the difference between two wells is that the diffusion of N_2O from water and air inside the well to the open ambient atmosphere. It may be possible that the deeper the well, more time need to diffuse N_2O to the atmosphere. These could explain that both processes of denitrification and diffusion might be more effective in the well 1 than the well 2 and far more in the puddle.

In the drain, high dissolved N_2O concentration observed was probably also due to increasing the denitrification process. As explained by Sawamoto *et al.* (2003), in cultivation onion area in central Hokkaido, the dissolved N_2O concentration was increased due to the denitrification process in the subsoil during and after nitrate leaching in the subsurface-drainage. NO_3^- concentrations in groundwater decrease as a result of increased denitrification in the riparian (Watts and Seitzinger 2000), and the increased denitrification by trading a decrease in NO_3^- transport to surface water for increased N_2O emissions (Groffman *et al.* 2000). Concentration of N_2O in the surface water of the drainage tended to be higher than in the well and puddle in the same level of NO_3^- concentration (Fig. 3.5), so it could be explained that the N_2O dissolved in water was evolved to the ambient air during water flow to downstream as reported by Minami and Fukushi (1984). It may also be explained by the location of sampling sites (Fig. 3.1) as drain 1(D1 (in 100 cm depth)) and well 1(W1) may be more close to the source of N_2O and fertilized area than drain 2 (D2 (in 200 cm depth)) and well 2 (W2), although more detail examination is needed in the sites.

N_2O emission factor from aquifers and agricultural drainage water (EF5-g) was corrected downward from 0.015 to 0.0025 by IPCC in 2006, based on the data of Reay *et al.* (2005) and Sawamoto *et al.* (2005). In this study, the EF5-g was determined lower in puddle than the IPCC (2006) default value, while it were higher in drains and in wells compared with the range of the IPCC default value. Dissolved N_2O concentration in drains observed higher than puddle and wells, as affected by water movement inside the drain. N_2O produced in flowing waters is rapidly emitted to the atmosphere due to high gas exchange rates and turbulent flows, whereas N_2O produced in reservoirs such as puddle and wells are likely to reside in the water body for a longer period of time where it may be further reduced to N_2. N_2O production in reservoirs is determined over longer time scales than in flowing waters (Beaulieu *et al*. 2014). And inside the drain, there is a number of processes remove N from the water column, including assimilation into microbial and plant biomass, sorption to sediments, and burial of particulate N (Wollheim *et al.* 2008).

The observed relationships between dissolved N_2O and NO_3^- suggest that emission factors were different in each location due to relation with denitrification rate, groundwater residence time, sampling depth, and water movement. It has been explained that denitrification rates and N_2O fluxes should be more closely examined in relation to drain geomorphology (depth, residence time), hydrology (residence time and flow), and the dynamics of the nitrate load over distance and time. A study by Reay *et al*. (2003) demonstrated how rapidly N_2O degassing from drainage waters can occur, indicating that degassing of N_2O already present in the groundwater (Clough *et al.* 2006). Principally, the vertical diffusive fluxes from the aquifer surface should be added to the potential total groundwater-derived emission (Deurer *et al.* 2008). Solid estimates of diffusive fluxes are thus needed in order to check if the inclusion of this path leads to higher emission factors as suggested by Weymann *et al.* (2009). Perhaps the most important criticism of the EF5-g value is in its application to open systems. This EF was adopted to help account for degassing of groundwater and water from drains, which can have very high concentrations of N_2O. However, because surface drainages, like puddle in this study, are open to gas exchange, rapid degassing of excess N_2O may occur and the ratio of N_2O-N / NO_3^--N may change over very short distances (Reay *et al.* 2003; Baulch *et al.* 2012). This study observed dissolved N_2O concentration tended to be higher in drains than that in puddle and wells. It could be explained that different values of EF5-g may related with feature of topography, since the sources of water was sampled in the different locations along the slope (Fig. 3.1).

Due to measurement in short time period in this study, there might be still uncertainties in the estimation of EF5-g. It is known that NO_3^- and dissolved N_2O are subject to interacting during subsurface transport in the water (Dobbie and Smith 2003b). Furthermore, determination of N_2O in the aquifers as an intermediate product from denitrification is permanently influenced by different enzyme kinetics of various denitrifying communities. Groundwater N_2O concentration is the net result of simultaneous production and reduction reactions (Well *et al.* 2005). So it is needed to conduct observation in long-time period for accurate and detail estimation of N_2O concentration in the aquatic ecosystem.

3.5.3 pH, dissolved CO_2 concentration and water quality

Value of pH from all water samples during the measurement were almost the same (Fig. 3.5). pH value varied seasonally, in June 2012 measurement during dry season showed a slightly higher of pH value in all water samples, while in October 2012 and January 2013 during wet season, the pH value decreased. Higher precipitation during wet season may initiate to attribute acidic condition in water source by decreasing pH value (Shabalala *et al.* 2013). The seasonal variation of pH values observed in this study was similar with result reported by Abowei (2010) in Nkoro river, Nigeria. The highest pH value showed in the dry season and lower pH value in the wet season. It was explained that seasonality of the pH water may be due to the influx and decay of debris in area and imbalance level of H^+ ions input from surface runoff during the precipitation. Precipitation is naturally acidic because of exposure to atmospheric carbon dioxide. As precipitation occurred, rainwater combines with carbon dioxide can influence the water toward acidity and pH is lowered (Wurts and Durborow 1992). Value of pH may change due to changes in photosynthesis and other chemical reactions. Photosynthesis uses up dissolved carbon dioxide, which acts like carbonic acid (H_2CO_3) in water. CO_2 removal, in effect, reduces the acidity of the water and so pH increases. In contrast, respiration of organic matter produces CO_2, which dissolves in water as carbonic acid, thereby lowering the pH (Michaud 1991).

Carbon dioxide is dissolved in groundwater and determination of dissolved CO_2 could be measured by indirectly method by monitoring in changing in pH where the CO_2 is dependent on shift pH value (Macpherson 2009). In this study (Fig. 3.5), dissolved CO_2 concentrations in all water sources were very low from the normal value in the natural reservoir (5 to 10 mg L^{-1}) (Wurts and Durborow 1992). The dissolved CO_2 concentrations were estimated by using indirectly calculation method by change of pH value (Lower 1996) which explained that the concentrations of dissolved CO_2 and pH values influence each other. Therefore it is complicated to explain which factors affecting in the different of dissolved CO_2 concentrations among the water sources sample, except by the pH value. Generally, groundwater has high CO_2 concentration, and low pH and oxygen concentration. CO_2 is high in groundwater because of bacterial process in the soils and various reactions in the groundwater, particulate mineral formations through water movement (Wurts and Durborow 1992). In the next future, directly measurement of dissolved CO_2 concentration by using a chemical test procedure from water sources is preferred, thus it can explain more detail factors affecting the dissolved CO_2 concentration accurately.

Concerning with water quality in this study, it described below by criteria of level of pH, NO_3^- and NH_4^+ concentrations in the water samples of the oil palm plantation area. The pH balance of a water supply describes how acidic or alkaline it is. The acidity or alkalinity of a water supply can affect plant growth, irrigation equipment, and drinking water suitability. Most natural waters are range from 5 to 8. The generally acceptable range of pH for irrigation water is between 5.5 and 8.5. While pH water quality standard for drinking water requiring disinfection only is 6.5 to 8.5 (Colin and McKean 1991). Based on pH standard criteria, the water sources in the oil palm plantation was slightly lower than which proposed by WHO (2008). The pH of drinking water is not health matters. However the acidic water or low pH is possible to leach metals from plumbing systems, which have potential to cause health problems (EPA 2001).

Chemical fertilizer application as anthropogenic sources of nitrogen contamination in groundwater from agricultural activities are significantly influence the water sources (Kumazawa 2002). In the most countries, nitrate levels in drinking water derived from surface water do not exceed 10 mg L^{-1}, although nitrate levels in well-water often exceed 50 mg L^{-1}. A high nitrate concentration in drinking water can cause methemoglobinemia in infants and in the stomach in adults (Gatseva and Argirova

2008). Ammonia in drinking water is not of immediate health relevance, and thus no health-based guideline value is suggested. Ammonia is, however, an indicator of possible bacterial, sewage, and animal waste pollution (WHO 2008). A high ammonia concentration has the potential to increase the nitrate concentration through nitrification. Generally, ammonia in the groundwater is below 0.2 mg L^{-1}, but anaerobic groundwater may contain ammonia up to 3 mg L^{-1}. The threshold odor concentration of ammonia at alkaline pH is approximately 1.5 mg L^{-1}, and a taste threshold of 35 mg L^{-1} has been proposed for the ammonium cation (WHO 2003).

Result of this study observed that from all water sources the mean of concentration of NH_4^+ and NO_3^- were 0.32 to 1.06, and 0.11 to 2.79 mg L^{-1}, respectively. Therefore, it could be stated that water quality in the area of plantation is in the range of standard based on criteria for drinking-water.

3.6 Conclusion

Topography affected spatial and temporal variation of N_2O and CO_2 fluxes in oil palm plantation. Soil properties such as NO_3^- and WFPS were explained most of cumulative N_2O flux variability, while cumulative CO_2 flux influenced by WFPS only. Topography even in a short slope affected N_2O and CO_2 emissions, therefore it may need to be taken into account in field measurements and modelling. Dissolved N_2O concentrations in water sources were supersaturated as leading to possibility to be source of indirect emissions and varied widely according to the locations and sampling situations. Agricultural landscape may play an important role in relation to hydrological process.

Table 3.1 Physicochemical soil properties in study site according to sampling time and slope positions

Sampling time	Slope Positions	TC	TN	NO_3^-	NH_4^+	pH	Bulk Density	WFPS
		(g kg^{-1}ds)		(mg N kg^{-1}ds)			(g cm^{-3})	(%)
Jun. 2012	Upper	18.8±0.75	1.60±0.08	5.86±0.96	8.51±0.55	4.93±0.42	1.15±0.01	57.4±4.94
	Middle	19.7±0.51	1.64±0.06	6.24±0.24	5.68±0.57	4.77±0.21	1.15±0.01	62.5±1.76
	Lower	21.3±0.92	1.79±0.12	7.47±0.81	9.26±0.35	4.35±0.25	1.12±0.02	74.6±4.14
Oct. 2012	Upper	21.8±1.67	1.78±0.24	8.16±0.71	10.8±0.41	4.21±0.63	1.13±0.02	51.6±3.08
	Middle	18.3±1.01	1.57±0.08	10.7±0.75	11.4±0.25	4.06±0.62	1.11±0.03	66.3±6.93
	Lower	20.2±1.33	1.69±0.10	19.1±0.83	14.5±0.56	4.09±0.23	1.12±0.03	76.0±2.29
Jan. 2013	Upper	22.9±1.50	1.88±0.13	4.05±0.73	11.4±0.07	3.90±0.12	1.11±0.02	61.8±2.25
	Middle	18.2±1.18	1.55±0.11	1.17±0.11	10.3±0.03	3.66±0.40	1.08±0.03	76.2±1.82
	Lower	18.8±0.98	1.59±0.07	14.6±0.57	9.54±0.36	3.94±0.22	1.09±0.01	78.6±2.78

Data are presented as the means ± standard deviation (n = 3). TC, total carbon; TN, total nitrogen; NO_3^-, nitrate; NH_4^+, ammonium; BD, bulk density; WFPS, water-filled pore space.

Table 3.2 Means of N_2O fluxes for the three slope position during wet and dry seasons

Slope position		N_2O flux (μg N m^{-2} h^{-1})	
		Wet season	Dry season
Upper		10.4±2.46	5.40±2.16
Middle		13.0±1.32	5.01±2.62
Lower		17.0±0.99	5.75±2.95
ANOVA	df	*F* value	*p* value
Seasons	1	99.106	<0.001
Slope	2	6.268	0.014
Seasons x slope	2	4.928	0.027

Data are presented as the means ± standard deviation (n = 3).

Wet season: from October to March; Dry season: from April to September.

Table 3.3 Means of CO_2 fluxes for the three slope position during wet and dry seasons

Slope position		CO_2 flux (mg C m^{-2} h^{-1})	
		Wet season	Dry season
Upper		71.8±10.9	89.4±10.1
Middle		79.7±11.2	99.1±13.3
Lower		77.1±9.41	114±9.14
ANOVA	df	*F* value	*p* value
Seasons	1	24.074	<0.001
Slope	2	3.095	0.082
Seasons x slope	2	1.593	0.243

Data are presented as the means ± standard deviation (n = 3).

Wet season: from October to March; Dry season: from April to September.

Table 3.4 Pearson correlation soil properties and cumulative nitrous oxide (N_2O) and carbon dioxide (CO_2) emissions by different slope positions (*n* = 9).

Soil parameters#	N_2O	CO_2
TC	0.074	-0.396
NO_3^-	0.729*	0.493
NH_4^+	0.371	-0.050
WFPS	0.704*	0.689*

TC, total carbon; NO_3^-, nitrate; NH_4^+, ammonium; WFPS, water-filled pore space;

* Significant at 0.05, # other soil parameters showed no significance.

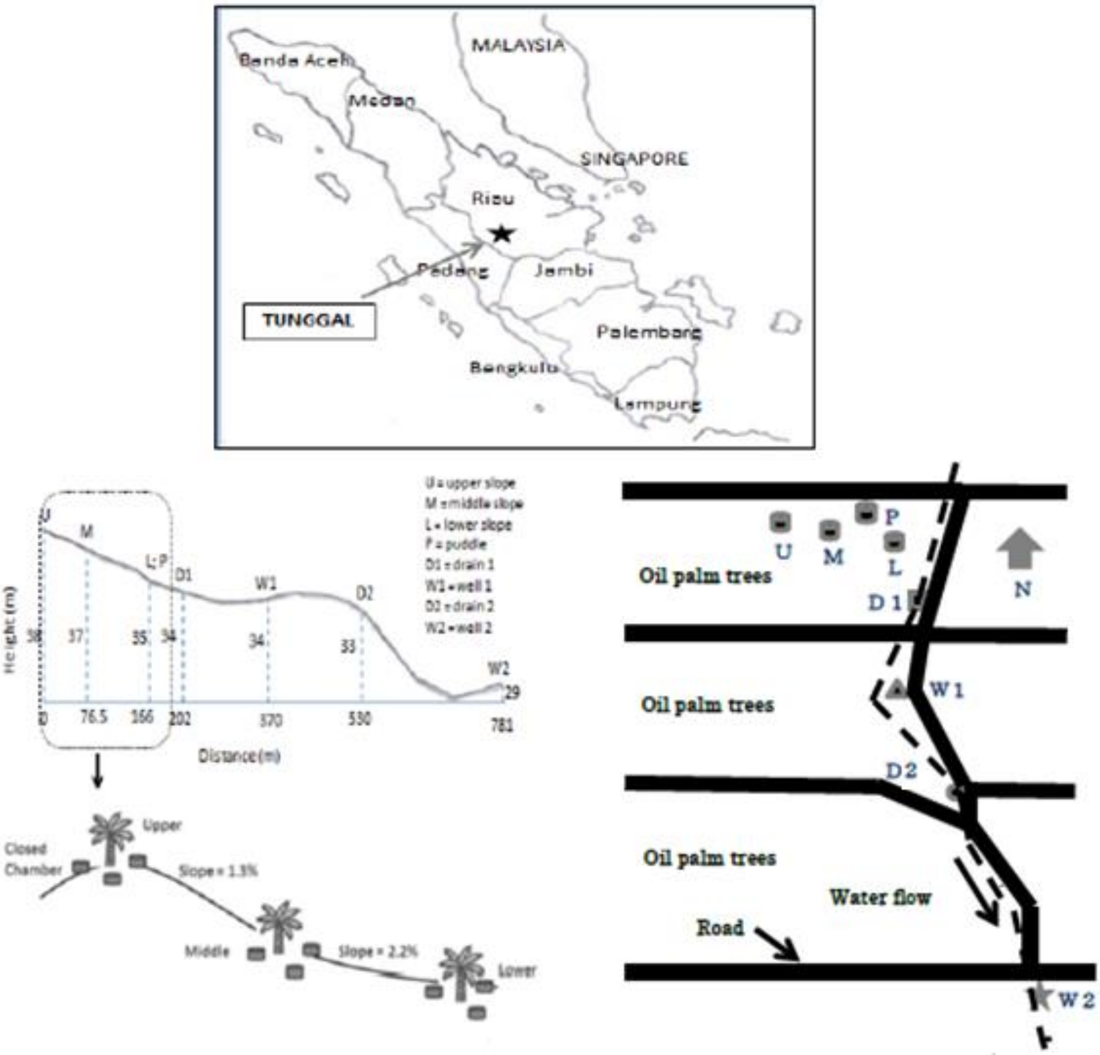


Figure 3.1 Map of study site at Tunggal Plantation, Riau Province and topography positions of data measurement.

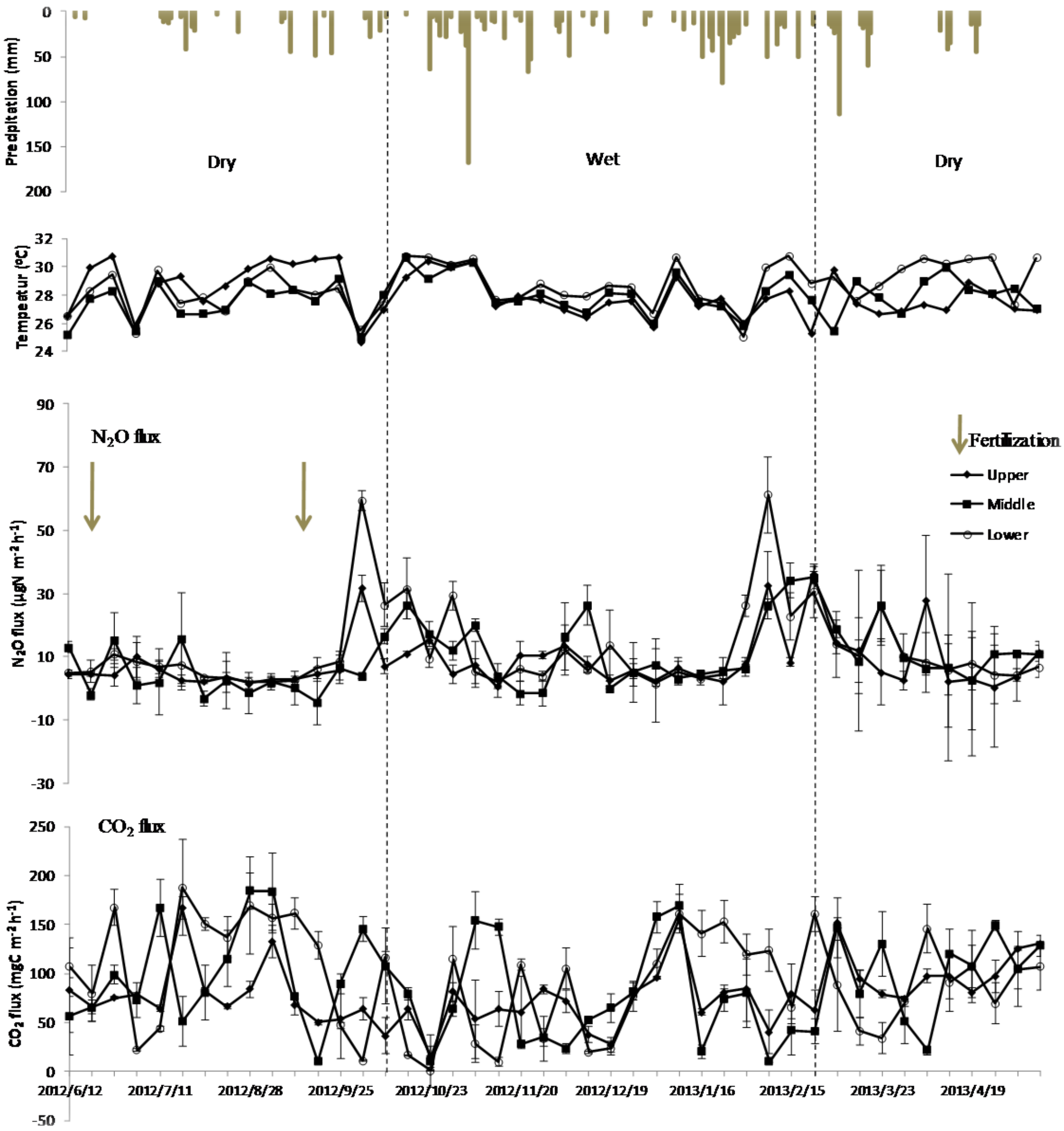


Figure 3.2 Precipitation, temperature, N_2O flux, and CO_2 flux in the upper, middle, and lower slope in Tunggal. Vertical bars ± indicated standard deviation (*n*=3). Solid arrows indicate fertilization timing. Vertical dashed lines indicate transition period for dry and wet seasons.

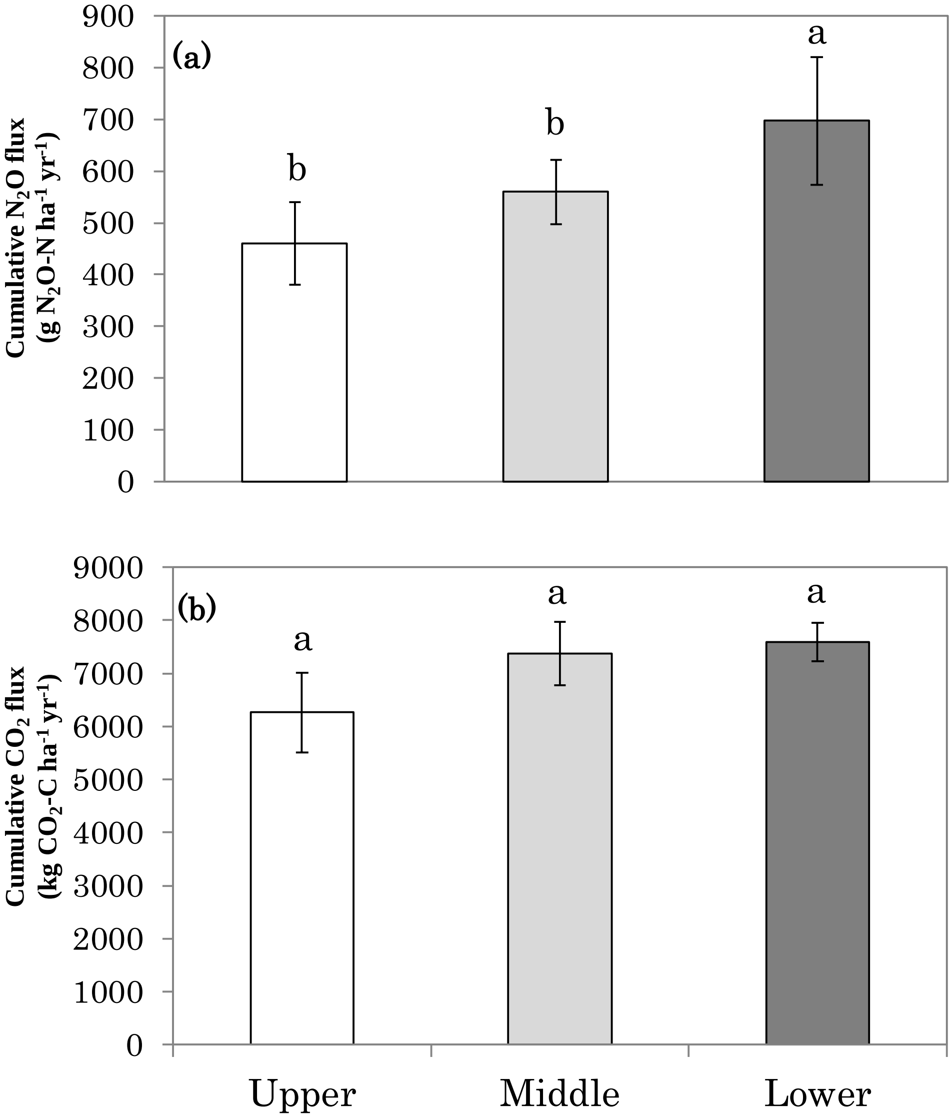


Figure 3.3 Cumulative nitrous oxide (N_2O) (a) and carbon dioxide (CO_2) (b) fluxes in the upper, middle, and lower slope positions. The vertical bars indicate the standard error (n = 3). Cumulative N_2O fluxes showed significant differences between slope were determined with a one-way ANOVA (p = 0.043) and are displayed as different letters. There was no effect of slope on cumulative CO_2 fluxes (p = 0.075)

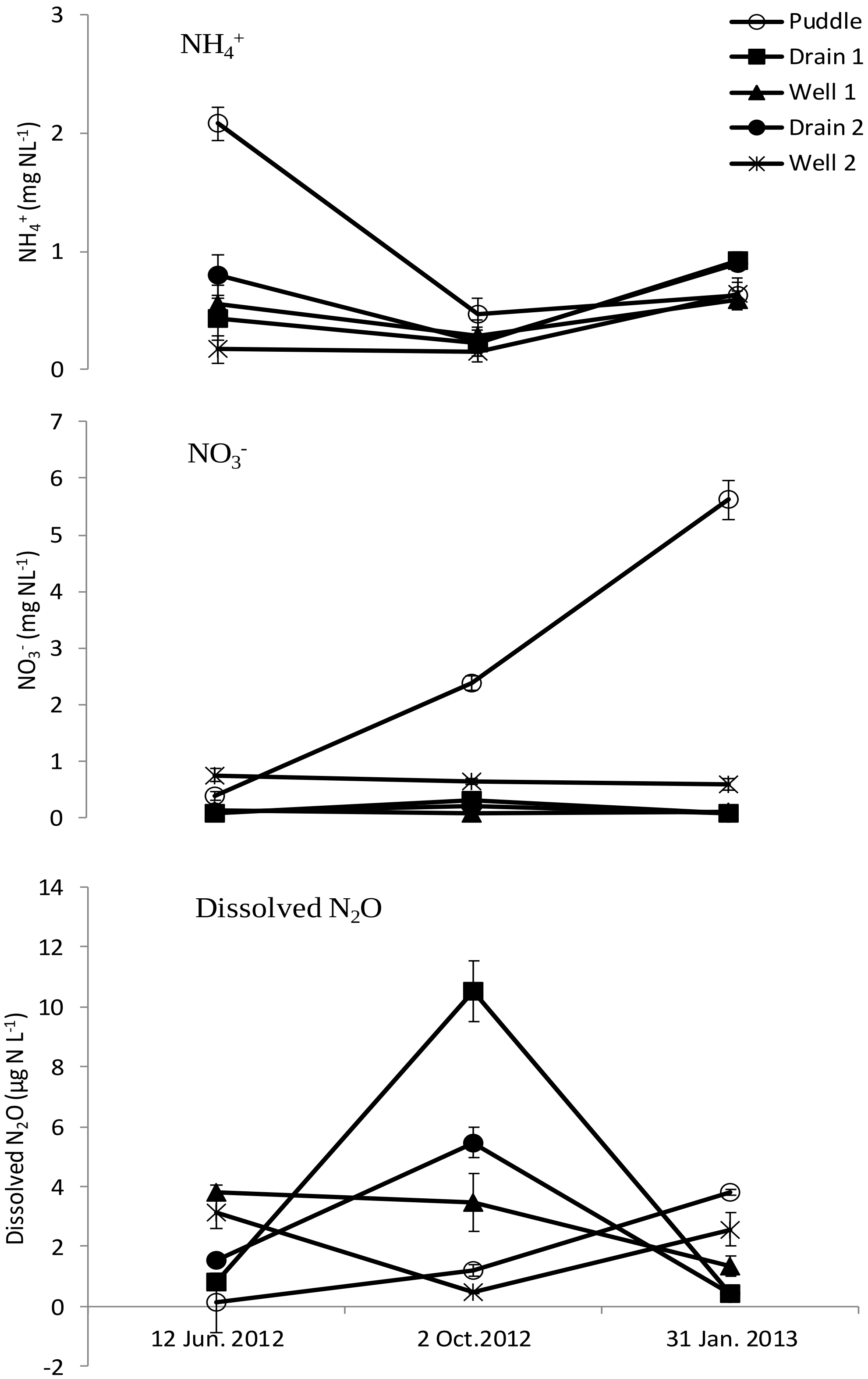


Figure 3.4 NH_4^+, NO_3^-, and dissolved N_2O concentrations in water samples. Vertical bars ± indicated standard deviation.

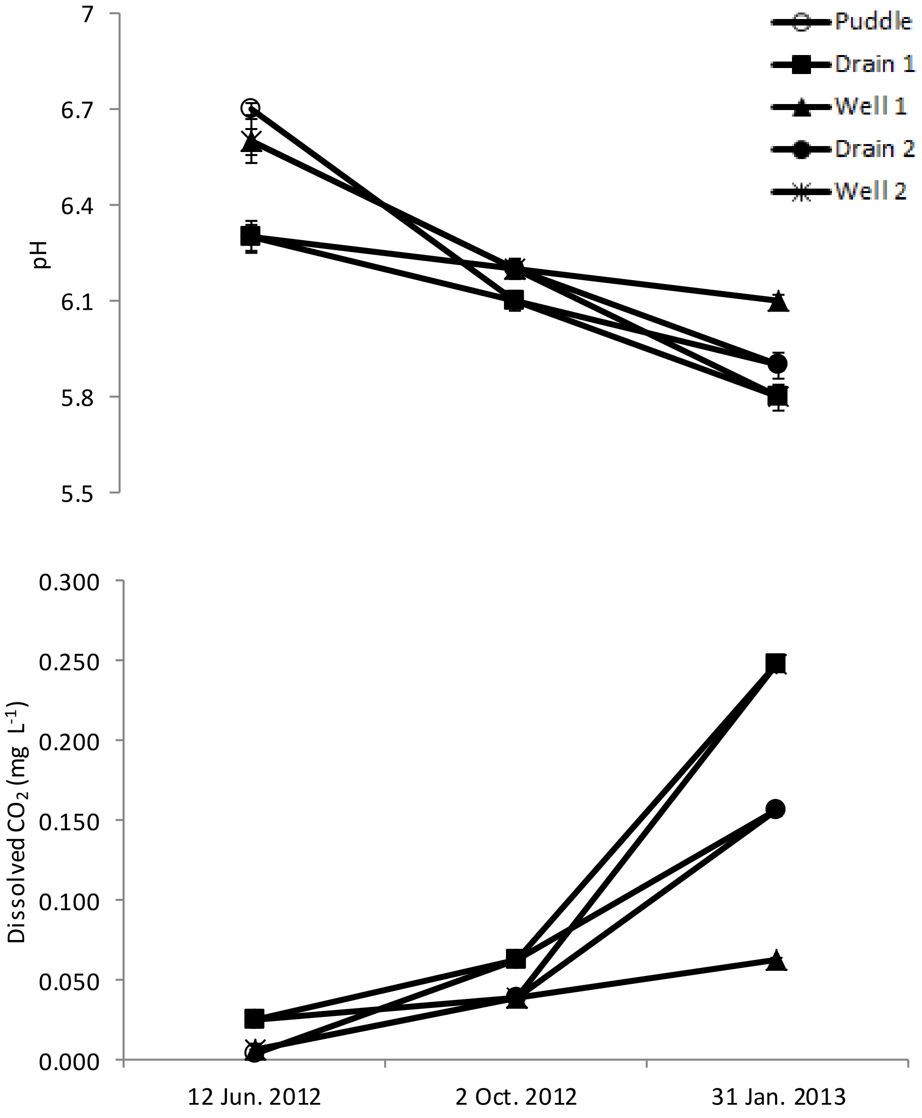


Figure 3.5 pH and dissolved CO_2 concentrations in water samples. Vertical bars ± indicated standard deviation.

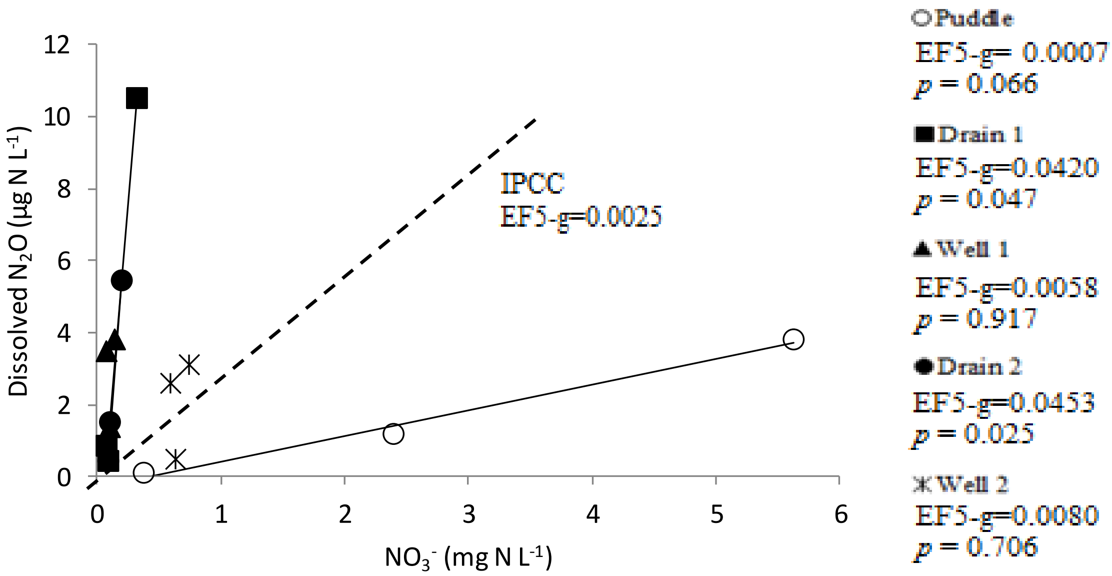


Figure 3.6 Relationship between NO_3^- and dissolved N_2O concentrations by source of water. EF5-g, emission factor for ground water; *p*, value of statistical linear regression.

Chapter 4

Effect of soil types and nitrogen fertilizer on yield in oil palm plantations

4.1 Abstract

In the oil palm plantation, one of the most important targets to be achieved is Fresh Fruit Bunches (FFB) yield. Oil palm depends on many interrelated factors which vary from one environment to another. Soils and fertilizers are essential factors on the growth and production of oil palm. This study aimed to determine effect of soil types and nitrogen fertilizers on FFB yield on mineral soil in Tunggal, Indonesia and in Simunjan, Malaysia, and also on peat soil in Tatau, Malaysia, from 2011 to 2012. Within each site, the N fertilizer applied with conventional and coated fertilizers. Dosage of coated fertilizer application was half and quarter of dosage from conventional fertilizer. FFB yields were recorded and summarized on an annual basis based on data collection. Results showed that by different dosage of conventional fertilizer and coated fertilizer had no different on FFB yields in each study area. Application of coated fertilizer with half dosage from dosage of conventional fertilizer were more effective on Partial Factor Productivity (PFP) as 53.2%, 45.4%, 49.1% and 57.1% in Tunggal, Simunjan, Tatau (immature), Tatau (mature), respectively. Application with quarter

dosage of coated fertilizer from dosage of conventional fertilizer showed that PFP by coated fertilizer was 72.9% more effective in Tunggal. Therefore, reducing the dosage of coated fertilizer in each soils type showed that coated fertilizer is more productive on FFB yields.

Key words: mineral soil, peat soil, fertilizers, FFB yields, PFP (see page 101).

4.2 Introduction

The oil palm is the most productive oil crop in the world. Despite the absence of mineral elements in the oil produced, large quantities of nutrients are used by the plant for its vegetative growth and its yields. Fresh Fruit Bunch (FFB) yield of oil palm plantation is the most important indicator in measuring the efficiency and effectiveness of the plantation. Yield of the oil palm plantation achieved at the same time can also be a measure whether the cultivated plantation industry is economically viable (Anwar *et al.* 2014).

Oil palms mature rapidly and fruit can be harvested as soon as 2-3 years after planting (Basiron 2007), although trees aged 9-15 years are the most productive (BisInfocus 2006). The FFB typically are 52% dry weight and have an extractable oil content of 15-25% depending on ripeness at harvesting time. Under optimal condition yields may reach 25-30 t FFB $ha^{-1}yr^{-1}$, and with an average extraction rate of 21-23% this corresponds with an approximate 6 t oil ha^{-1} (Verheye 2010). Harvesting rounds should be made as frequent as possible to avoid over ripening of bunches. Harvesting rounds of 7-14 days are generally practiced. Under well-managed conditions, 10-15 bunches can be harvested per palm per year, weighing 15-20 kg each, total yields are 13-30 $ha^{-1}yr^{-1}$. The typical commercial lifespan of an oil palm is approximately 25 years. After 25-30 years trees become too tall to harvest and are replaced (Basiron 2007).

Regarding to the soil type, oil palm have a reasonably high tolerance and can grow at the diverse soil characteristics soil with a fairly wide interval on various soil types ranging from organic soil of Histosols to mineral soils of Andisols, Oxisols, Entisols, Inceptisols and Ultisols. Histosols are known by various other names in other countries, such as peat or muck (Anwar *et al*. 2014), as long as it is well watered (NewCROP 1996). In Indonesia and Malaysia, the oil palm is mainly planted on highly weathered soils which belong to the orders Ultisols and Oxisols (Shamshuddin *et al.* 2015). These soils exits under tropical environment which are subjected to high rainfall and temperature throughout the year, therefore the soils are predominantly acidic and deficient of macronutrients or low in fertility (Shamshuddin and Anda 2012). Consequently fertilizer input is very necessary applied regularly at the appropriate rate.

Oil palm needs humid equatorial conditions to thrive, and soil and climatic conditions play roles in the growth of oil palm, hence conditions in Indonesia and Malaysia are suitable for its uninterrupted growth (Basiron 2007).

Fertilizers are crucial in oil palm production, accounting for 50–70% of field operational costs and about 25% of the total cost of production (Caliman *et al.* 2007; Goh and Hardter 2003). Especially during the fruiting season, oil palms is requiring high amounts of nutrients which are contain N, P, K, Ca, Mg and S as well as micronutrients such as boron, copper, zinc, iron and manganese and molybdenum (IPI 1991). Nitrogen is the most important nutrient for oil palm growth and a key input to food production. Nitrogen is required for the formation of protein (IPI 1991). The potential needs of the crop at level of growth and yield must be determined in order to draw up an appropriate and balanced fertilizer use (Foster and Dolmat 1986). In the management practices, approaches to improve crop nutrient use efficiency and fertilizer efficiency is very important (Aziz and El-Asry 2009; Prasad 2009). Significant improvements must be made in N use efficiency to produce enough yields and to avoid large-scale degradation of ecosystems caused by excess N (Tilman *et al.* 2001).

To determine the efficiency of applied nutrients, Cassman *et al.* (1996) introduced the term Partial Factor Productivity (PFP). The advantage of this index is to quantify total economic output from any particular factor or nutrient, relative to its utilization from all resources in the system, including indigenous soil nutrients and nutrients from applied inputs. The PFP for N over the years can be used to indicate the sustainability of the oil palm production system. Therefore, the objective of this study was to determine the effect and efficiency of reducing fertilizer rate of coated fertilizers compare to conventional fertilizer on FFB yield in different soil types.

4.3 Materials and Methods

Study sites were located in oil palm plantation areas on tropical land, in Indonesia and in Malaysia from 2011 to 2012. The one site was located in Tunggal on sandy loam soil, and other 2 sites were located in Simunjan on sandy soil and in Tatau on peat soil, respectively. The annual rainfall is about 1387, 4095, and 2225 mm in Tunggal, Simunjan, and Tatau, respectively. Physicochemical properties of the soils were described in chapter 2. Growth of oil palm plantation was monitored by measuring the production of FFB according to age of oil palm in each study sites. The N fertilizer rates applied were as conventional rate as plantation practices (C), coated fertilizer with half (M1) and quarter (M2) dosages of conventional fertilizer (Table 4.1). The conventional fertilizer was applied by surface-placed on the ring under the canopy of palm, while the coated fertilizer applied in the 4 holes (in 10 cm depth) under the canopy of palm. Area studied are consisted with 525 palms (mature, 7 years) in 3.9 ha in Tunggal, 50 palms (mature, 9 years) in 0.37 ha in Simunjan, 40 palms (immature, 4 years) in 0.27 ha, and 48 palms (mature, 5 years) at 0.32 ha in Tatau (Figure 4.1). FFB yields were recorded and summarized on an annual basis based on data collection. To compare the efficiency of N applications, the PFP was analyzed for each fertilizer treatments in each study site.

Partial Factor Productivity (PFP) is determined the efficiency of applied nutrient (Goh *et al.* 2003) and it was calculated as below by Cassman *et al.* (1996):

PFP = Y/Na

Where Y is FFB yield (kg ha^{-1}), (Na) is N applied (kg ha^{-1})

4.4 Results

As described in Chapter 2 already, soils of each site have different in physicochemical characteristics. Based classification of soil nutrient content for oil palm, soil condition in each site is described in Table 4.2. Soil pH, total C and total N on mineral soil both in Tunggal and Simunjan was categorized as “high”. On peat soil, pH was categorized as "very low", while total C and N was categorized as "very high" according to Goh (2005) Table 4.3.

Fresh Fruit Bunch (FFB) weight is described in Fig. 4.2. The FFB calculated in Tunggal as harvest day average, in Simunjan as quarterly average, in Tatau as monthly average. Result showed that accumulation of FFB production by different dosage of conventional fertilizer and coated fertilizer had no different in each study area. Annual FFB production in each study area showed that treatment with coated fertilizer by a half of conventional fertilizer dosage were higher compared with conventional fertilizer treatment. Annual FFB production in Tunggal was 10185, 10958, and 9561 kg ha^{-1} yr^{-1} in C, M1, and M2 fertilizer applied, respectively. Annual FFB production in Simunjan was 10959 and 11622 kg ha^{-1} yr^{-1} in C, and M1 fertilizer applied, respectively. Annual FFB production in Tatau for immature was 8963 and 9170 kg ha^{-1} yr^{-1} and for mature was 8880 and 9270 kg ha^{-1} yr^{-1} in C and M1 fertilizer applied, respectively (Fig. 4.3). Results show that coated fertilizer showed same pattern in each type of soil in increasing FFB production even if applied a half of conventional fertilizer.

By applying N fertilizer, the PFP with conventional fertilizer and coated fertilizer can be compared. Result showed by applied half dosage of conventional fertilizer that PFP by coated fertilizer were more effective 53.2%, 45.4%, 49.1 % and

57.1% in Tunggal, Simunjan, Tatau (immature), and Tatau (mature), respectively. And by applied a quarter dosage of conventional fertilizer showed that PFP by coated fertilizer was more effective 72.9% in Tunggal (Fig. 4.4). By reducing the rate of coated fertilizer in each soil type and age of palm, showed that coated fertilizer is more effective. PFP explained how much of yield is produced for each kg of nutrient applied.

4.5 Discussion

Soil pH is important because it can influence nutrient availability. A pH range of 5.6–6.0 is “optimal”. Areas with pH <4 or >7 are “unfavorable” for the oil palm (Stenek and Connell 2011). In this study, soil pH on mineral soil both in Tunggal and Simunjan was categorized “high” but still in the optimal range for oil palm. While on peat soil classified as “unsuitable”. Even the soil pH is very low seems no problem in oil palm growth. As explained by Auxtero and Shamshuddin (1991), with appropriate management, oil palm plantations can be productive on a wide range of soils, including “problem soil” such as acid sulphate soils, deep peat and acidic high aluminium soils, where few other crops are successful. There were large hectares of peat land being development for agriculture uses due to the high contents of C and N as well as other nutrient in peat soil. Generally total nitrogen contents in peat soil are high that compared with mineral soil. Moreover, it has been reported that FFB yield prospects on peat soil can be similar with FFB yields generated by oil palm cultivated on mineral soils (Fang and Jun 2014). There is evidence from plantations in Central and West Kalimantan that large yields can be achieved even on soils of low fertility status provided sufficient mineral fertilizer is applied to correct nutrient deficiencies, coupled with use of cover crops, recycling of empty bunches and other proper agronomic practices (Fairhurst and McLaughlin 2009).

Regarding to fertilizers type, comparing with conventional fertilizer, coated fertilizer have a coating protects the nutrients from leaching and volatilisation while the release pattern matches the plants needs during the growing cycle. Plausible reason could be put that run-off of losses of surface applied fertilizer such as broadcasting onto the palm circles, N uptake by the palms would be much lower resulting in poorer palm growth and production as experienced in the experiment (Kwan 2002). It reported that by burying fertilizer one can reduce its application by 20% to account for no runoff losses (Cheong *et al*. 2000).

Compared with uncoated urea, the coated urea had improved early palm growth. It is clearly showed that utilization of coated urea showed better result in girth size and front length for immature (1 to 3 years) oil palm growth. Therefore coated urea fertilizer can be used as alternative urea fertilizer especially for the dry regions where the volatilization rate occur a higher rate (Rasid *et al.* 2014). Therefore, even by reducing the fertilizer rate of coated fertilizer compared to conventional fertilizer, FFB of oil palm were almost similar in each soil types.

Any difference in FFB yield responses to methods of N application were probably a function of soil loss process, nutrient uptake and nutrient demand (e.g. higher demand during high cropping years). The soil losses process are mainly caused by runoff and leaching (Goh *et al.* 1999), nutrient uptake rate is generally influenced by root length, soil nutrient concentration and soil water content (Tinker and Nye 2000), and nutrient demand is dominated by oil palm growth and production. According to Cassman *et al.* (1996), PFP can be increased by increasing the amount, uptake and utilization of indigenous nutrients, and by increasing the efficiency with which applied nutrients are taken up by the crop and utilized to produce yields.

Karim and Ramasamy (2000) suggested that higher fertilizer use efficiency which is always associated with low fertilizer rate and cultural practices which meant for promoting integrated nutrient management. It will help to effect saving in the amount of fertilizer applied to the crops and there to improve fertilizer use efficiency. Resin coats have better control of the fertilizer release. Polymer coats also look promising for widespread use in agriculture because it can be designed to release nutrients in a more controlled manner by manipulating properties of polymer coating. It is hypothesized that the volatilization rate and nutrient leaching of urea fertilizer can be minimized and improved fertilizer efficiency can be achieved as compared to conventional urea fertilizer. Concerning with N_2O emission, coated fertilizer was effective to reduce N_2O emissions by 31 and 48% in wet and dry seasons, respectively, compared to the conventional fertilizer in Tunggal plantation on mineral soil. However, the effectivity on reducing N_2O and CO_2 fluxes in tropical oil palm plantation not always by fertilizer treatment, but it more significantly affected by the types of soil as explained in the Chapter 2.

Fertilizers are usually the largest variable cost item in oil palm production and therefore, it should be used at the highest possible recovery efficiency by minimizing soil nutrient losses. Every effort and input in the plantations should be geared towards producing the optimum or maximum yields. Including fertilizer, yield depends on a variety of factors, such as soil and climatic conditions, age, seed quality, and quality of plantation management.

4.6 Conclusion

Due to adaptability of oil palm to cultivate in wide range of soils types, oil palm can be grown and produce yield of FFB on mineral and peat soil. The yield supported by high content of nitrogen, carbon, and others nutrient in the soil. Considering to the growth of oil palm, applying coated fertilizer even with almost half rate and quarter rate in Tunggal, were effective to support yield of FFB of oil palm plantations. Coated fertilizer was effective to produce FFB on mineral and peat soils.

Table 4.1 Application of fertilizer in each study sites.

Study sites	Dosage (kg N ha^{-1})	Measurement period	Age of palm trees
Tunggal	151(C) 76(M1) 38(M2)	2 Nov. 2011 - 30 Oct. 2012	7 years (mature)
Simunjan	107(C) 62(M1)	1st-4th Quarter (2011-2012)	9 years (mature)
Tatau	69(C) 36(M1)	11 Nov. 2011 - 12 Dec. 2012	4 years (immature)
	87(C) 39(M1)	11 Nov. 2011 - 12 Dec. 2012	5 years (mature)

C; conventional fertilizer, M1; coated fertilizer with half dosages of conventional fertilizer, M2; coated fertilizer with quarter dosages of conventional fertilizer

Table 4.2 Soil fertility condition in each study sites based on classification of soil fertility for oil palm

Description	Study Sites		
	Tunggal	Simunjan	Tatau
Soil type	Mineral (Ultisols)	Mineral (Ultisols)	Peat
pH (KCl)	4.67±0.10 (high)	4.77±0.06 (high)	3.34±0.08 (very low)
Total C (%)	2.34±4.71 (high)	1.85±0.56 (high)	46.7±71.0 (very high)
Total N (%)	0.217±0.31 (high)	0.170±0.26 (high)	1.72±3.90 (very high)

Table 4.3 Classification of soil nutrient status for oil palm (adapted from Goh 2005)

Properties	very low	low	moderate	high	very high
pH	<3.5	3.5 - 4.0	4.0 - 4.2	4.2 - 5.5	>5.5
Total C (%)	<0.8	0.8 - 1.2	1.2 - 1.5	1.5 - 2.5	>2.5
Total N (%)	<0.08	0.08 - 0.12	0.12 - 0.15	0.15 - 0.25	>0.25

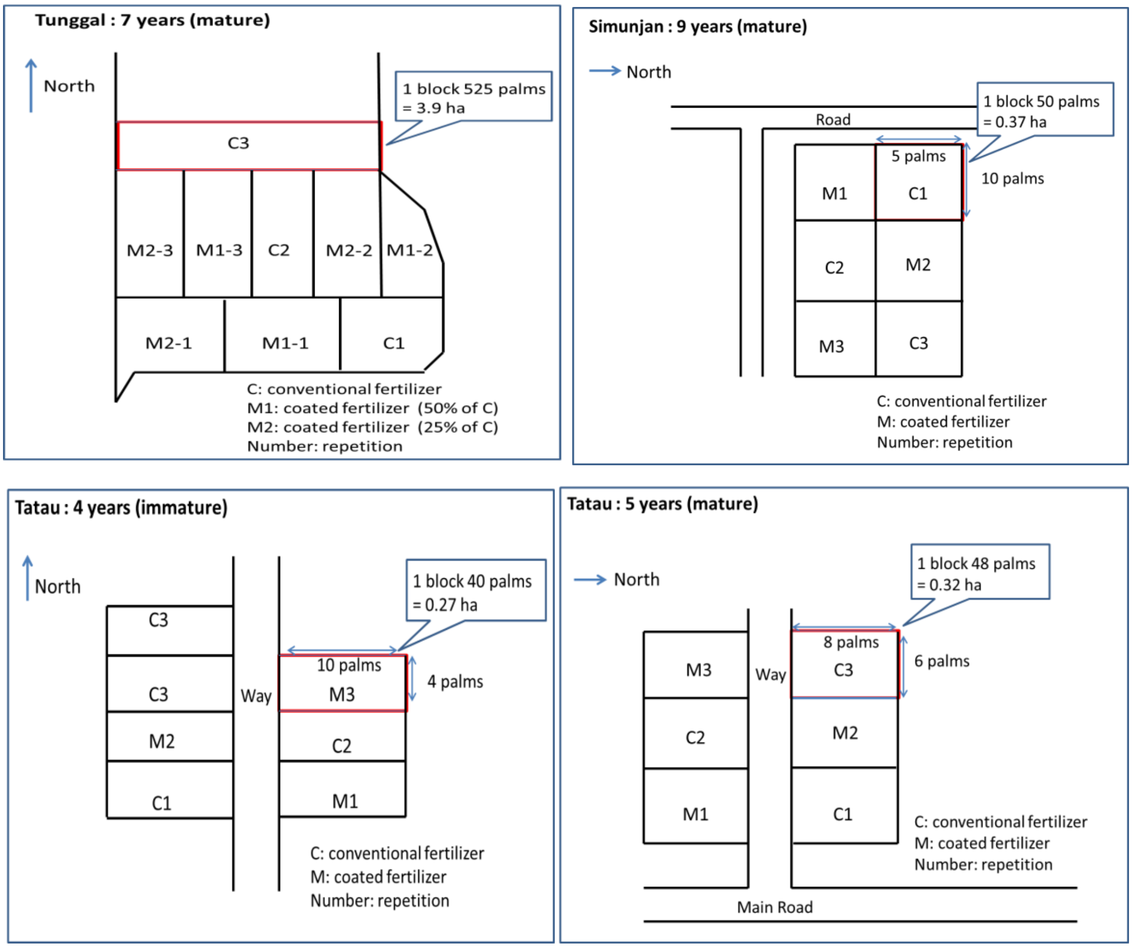


Figure 4.1 Layout of each treatment in study sites

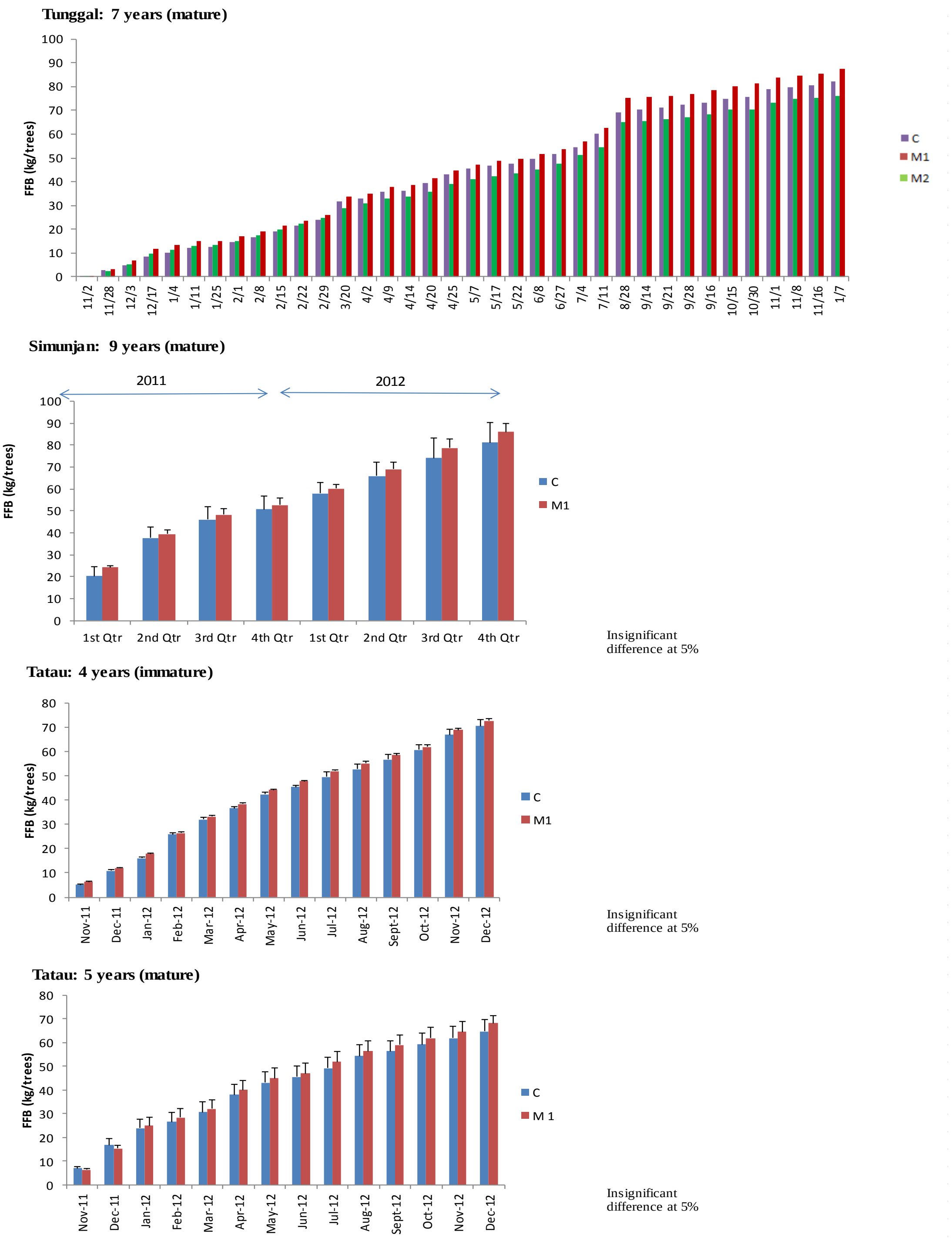


Figure 4.2 Accumulation of FFB productions per palms in each site study by different fertilizer treatments. C; conventional fertilizer, M1; coated fertilizer with a half of C dosage, M2; coated fertilizer with a quarter of C dosage

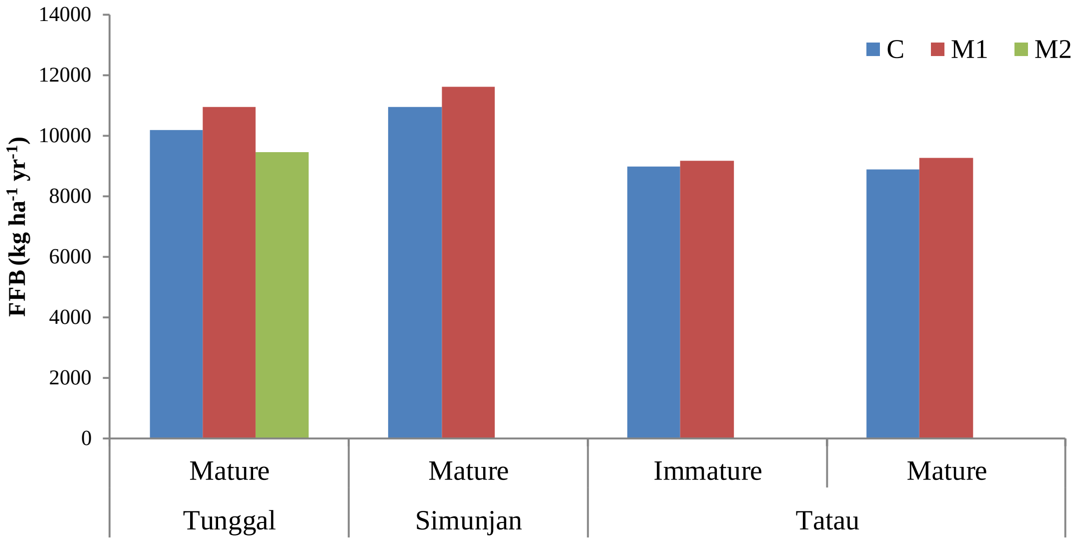


Figure 4.3 Annual FFB productions in each site study by different fertilizer treatments. C; conventional fertilizer, M1; coated fertilizer with a half of C dosage, M2; coated fertilizer with a quarter of C dosage

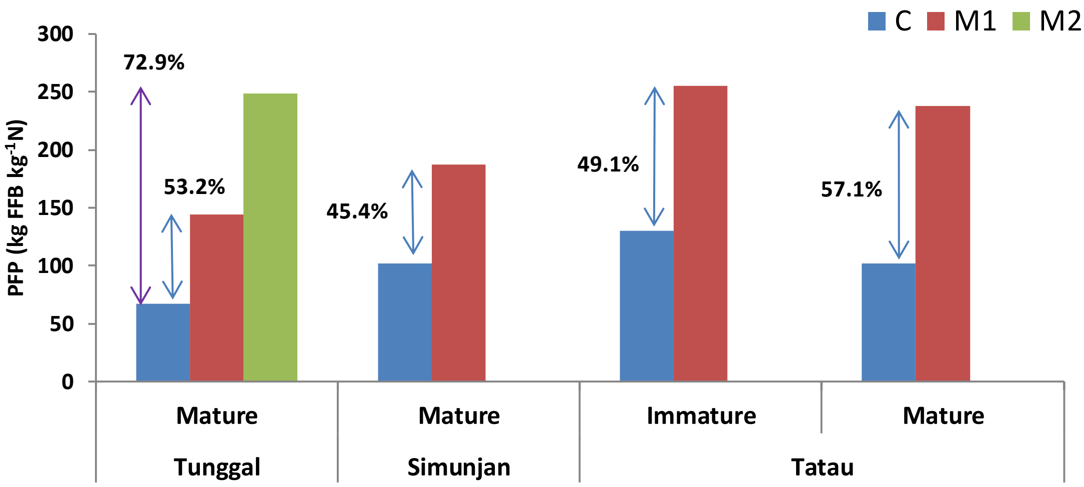


Figure 4.4 Partial Factor Productivity (PFP) in each site study by different fertilizer treatments. C; conventional fertilizer, M1; coated fertilizer with a half of C dosage, M2; coated fertilizer with a quarter of C dosage

Chapter 5

General Discussion and Conclusions

5.1 General Discussion

Climate change have been became an important environmental topics which related the agricultural sector. It well known that anthropogenic activities in the agricultural sector is considered as the sources of GHGs emissions. On agricultural sector, oil palm plantation has been increased as the sources of GHGs emissions through land use change and agricultural practices as introduced in the chapter 1 of this study. Whereby, agriculture sectors contribute 60% from anthropogenic N_2O sources (IPCC 2007; Schmidt 2010). In Indonesia and Malaysia, expanding large area of oil palm plantation has been increased critics concern due to its potential impact to induce GHG emissions. Among those sources, land use change and land preparation by burning method are serious problem and became the most important factor define level of GHG emission. Especially, when oil palm plantations are developed on peat soil, the carbon is lost as CO_2 because of oxidation of the peat soil due to drainage, fires and loss from biomass due to clearing vegetation (Arina *et al.* 2013). In Indonesia the largest land use change was from forest to oil palm, while in Malaysia oil palm development has been mainly at the expense of other permanent crops, rather than directly from deforestation (Wicke *et al*. 2008b).

Another source of GHGs emissions related to the expanding oil palm plantations practice is the application of N fertilizers (Yew *et al*. 2012). The application of N fertilizers in oil palm plantation may result in high acceleration release of N_2O emission into the atmosphere, and eventually leading to significant global warming. N_2O is an important greenhouse gas, due to its high global warming potential (298 times higher than CO_2). The use of N-fertilizer is important to provide that plants reach a desirable yield, on the other hand, a portion of this added N can be lost to the atmosphere as N_2O, enhancing the greenhouse effect. The increase in available mineral N in soil may enhance the formation of N_2O through the process of nitrification and denitrification (Hewitta *et al*. 2009). According to Treseder (2008), fertilization has strong effect not only N_2O emission but also on CO_2 emissions. Due to N-fertilizer is also applied to enhance the root respiration for rapid plant growth and generally will lead to the increasing of total CO_2 emission in the atmosphere. Soil CO_2 emissions are usually larger in the growing season because of higher carbon inputs from plant photosynthesis and more suitable microclimatic environment in soils for microbial decomposition. Soil CO_2 emission is basically controlled by two processes: CO_2

production within the soil and its transport from the soil into the atmosphere (Fang and Moncrieff 1999). Microbial activity and root respiration are the major sources of CO_2 production, and the transport of the gas is controlled by diffusion.

In fact, the amounts of N_2O emitted from soils depend on complex interactions between soil properties, climatic factors, topography and agricultural practices. The proportion of N_2O gases emitted from soils is influenced by soil type. On mineral soil, clayey soils tend to show greater N_2O emissions than sandy soils. N_2O emission increases with higher clay content of the soil, because the chance on anaerobic conditions increases (Velthof and Oenema 1995). It reported that under maize land, it found much higher N_2O emissions on clay soil compared to sandy soil (Van Groenigen *et al.* 2004). Peat soils have higher N_2O emissions than clay and sandy soils because of the higher organic matter content with related higher denitrification potential (Velthof *et al.* 1996). In the chapter 2 of this study, N_2O emission more affected by soils type rather than by fertilizers type. The highest mean of N_2O fluxes on peat soil in Tatau plantation, Malaysia, followed by sandy loam soil (5% content of clay) in Tunggal plantation, Indonesia and sandy soil (0.03% content of clay) in Simunjan plantation, Malaysia. N_2O emissions were not always affected by application of fertilizers whether by conventional fertilizer or coated fertilizer. However, on sandy loam soil in Tunggal plantation, Indonesia, application of coated fertilizer reduced N_2O emissions during wet and dry seasons. Concerning with CO_2 fluxes, it tended to increase with the increase in oil palm growth, higher root biomass would release in higher root respiration. On the climatic factor, precipitation is an important indicator for the risk of anaerobic conditions in soils. Many studies found significantly positive correlations N_2O emissions with precipitation and soil moisture (Smith *et al*. 1998; Zhang and Han 2008). In this study, high of N_2O fluxes appeared after a heavy precipitation. During the wet season, diffusion is no longer restricted and the accumulated inorganic N becomes available for microbial activity throughout the soil, which rapidly exploits the N pools and emits N_2O into the atmosphere (Melling *et al*. 2007).

Topography is one of the factors which effect of N_2O and CO_2 emissions. The highest N_2O emission is observed in the lower slope position where optimal water-filled pore space (WFPS) is encountered. Related with WFPS, high N_2O emission at the lower slope position may be driven by the denitrification pathways (Pennock *et al.* 1992; Izaurralde *et al.* 2004). Besides the N_2O emission into the atmosphere as direct emission, the important of N_2O emission from farmland drainage water as indirect emission is poorly understood. Indirect N_2O emissions account for one third of the total global agricultural N_2O source and approximately two thirds of the uncertainty in the total source (Mosier *et al.* 1998). It reported that on the drain water, the dissolved N_2O was very quickly lost to the atmosphere. Supersaturated concentrations of N_2O in groundwater and in surface water draining agricultural lands may occur due to leaching of NO_3^- from the soil towards drainage and groundwater, or production during nitrification and denitrification of fertilizer N in the groundwater or drainage. In the chapter 3 of this study, it explained that topography was correlated with N_2O emission. It observed that higher N_2O flux in the lower slope compared to upper and middle slope position. Concerning with concentration of dissolved N_2O in water resources, it observed in the supersaturated concentration as leading to possibility to be source of indirect emission.

Regarding with fertilization, it have to be considered the best practice for oil palm development to involve investigation on the soil, through a study to assess the potential affecting the GHGs emissions and increasing the efficiency of fertilizer N on FFB yield. High FFB yields are sustained in soil with high and balanced nutrient status (Goh 2005). In the Chapter 4 of this study, regarding with the fertilizers types in effectivity to produce high FFB, it described that application of coated fertilizer was more productive on FFB yield compared to conventional fertilizer on each soil types. Considering both of effect of fertilizer toward environment and growth of oil palm, it was explained that by applying coated fertilizer were effective to support production the FFB of oil palm plantation. However to mitigate the gas emission to the atmosphere, it is still needed careful attention with the suitability of soil types.

Since oil palm sector has been increased and created new jobs as well reduced poverty both in Indonesia and Malaysia, it seems that expanding oil palm plantations are still increasing in the future. As the oil palm is a perennial crop, it is important to understand how to improve intensive cultivation and to decrease the negative effect in the environment. On sandy loam soil based on the result in improve fertilizer efficiency and reduce N_2O emission, as compared to conventional fertilizers, the use of coated seems to be promising to utilize in oil palm plantation. However on peat soil, due to large amounts of N content, the application rate of N fertilizers should be considered carefully. With high organic carbon content and high ratio of C/N, affecting N mineralization on peat (Lim *et al.* 2012), as the result peat soils may release high amount of N from the second year after planting onwards, therefore the N application rate should be reduced (Corley and Tinker 2003). Application rate of N fertilizer on peat soil consider to be lower compare to mineral soil, as recommended by Ng (2002), N application rate for Ultisols and Histosols (peat soil) as 0.8-1.0 and 0.6-0.8 kg $palm^{-1}$ yr^{-1}, respectively. By carefully management of oil palm, the FFB yield obtainable to harvest for about 25 years once planted in the plantations. Due to old age, when the oil palm had reached the time for no longer valuable, the palms need to be replanted. The zero burning is recommended during the process of replanting to decrease the negative impact to the environment. In the practice of zero burning, Bakar *et al.* (2011) suggested utilization of the trunk, leaves, and empty fruit bunch (EFB) to be buried in the ground in the oil palm area. That technique will accumulate biomass and increase organic matter, so it could improve and maintain soil fertility.

By improving agriculture management, oil palm plantation on mineral and peat soil can be carried out sustainably on properly by long term observation. Further detailed study to asses a more accurate interpretation of the mechanism of N_2O and CO_2 fluxes in oil palm plantation and FFB yield is needed.

5.2 Conclusions

Based on situation of oil palm expansion and increasing GHGs (Chapter 1), it could be concluded as follows (Fig. 5.1):

- Soil types are affecting N_2O and CO_2 emissions comparing to the fertilizer types. However, depend on soil types, coated fertilizer have potential to reduce N_2O emission. (Chapter 2)

- N_2O emission is affected by topography, and ground water on the agriculture land have to considered carefully in calculating dissolved N_2O concentration as a source of indirect emission. (Chapter 3)
- The effectiveness fertilizer type to produce high FFB yield on various soil types both on mineral and peat soil showed that coated fertilizer is more effective than the conventional fertilizer. (Chapter 4)

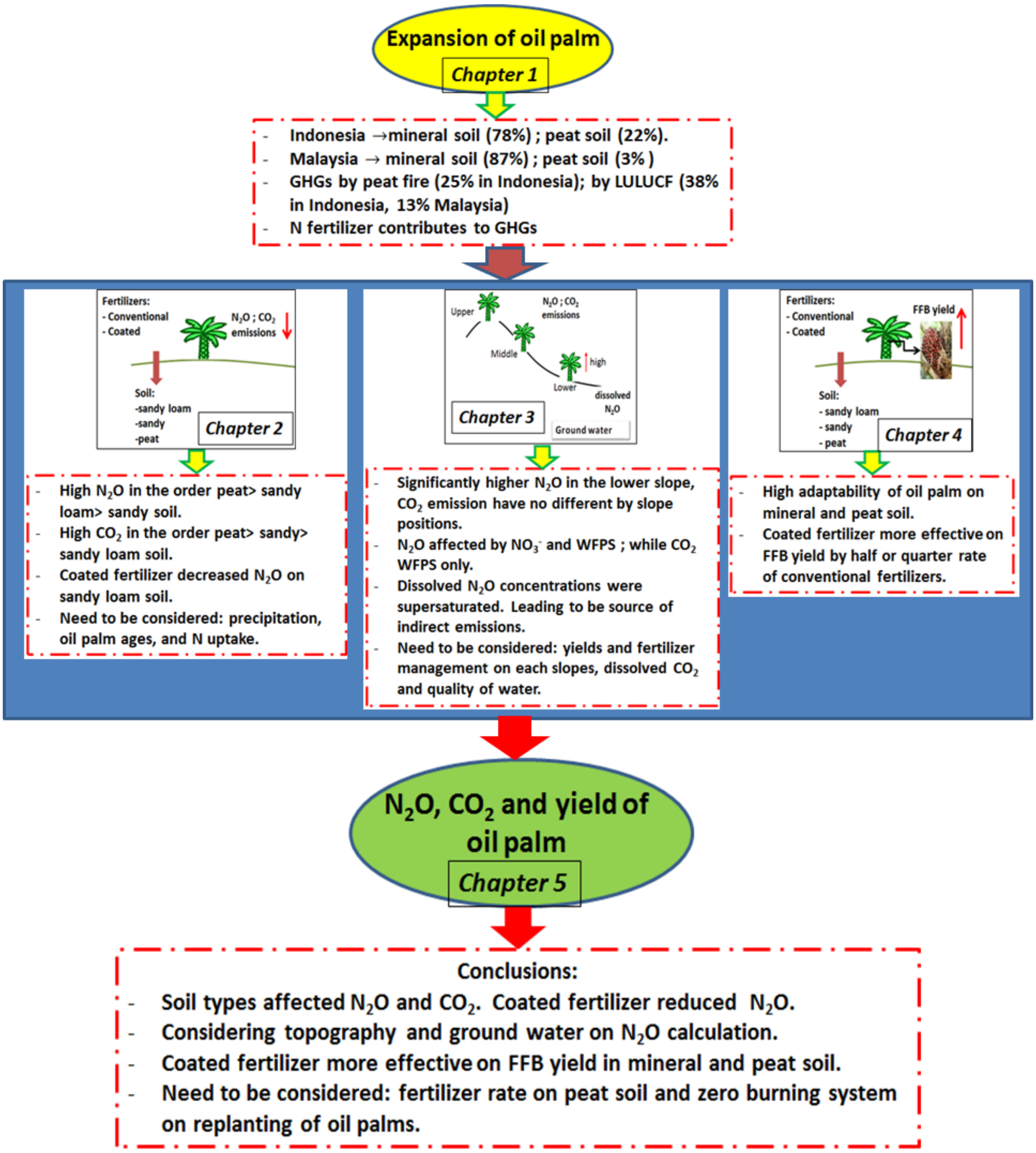


Figure 5.1 General conclusions of studies on soil, fertilizer and topography affect N_2O, CO_2 and yield of oil palm in Indonesia and Malaysia.

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