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ORIGINAL ARTICLE

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

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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 (N₂O) 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 N₂O and carbon dioxide (CO₂) emissions. This study aimed to evaluate the effects of soil types and N fertilizer on N₂O and CO₂ emissions in oil palm plantations. N₂O and CO₂ emissions were measured for 15–16 months from 2010–2012 in Tunggul 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. N₂O and CO₂ fluxes showed high variabilities with seasons, types of soil and fertilizer treatments. The mean of the N₂O 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 $\mu\text{g N m}^{-2} \text{h}^{-1}$ in the wet and dry seasons, respectively. The mean of the N₂O fluxes from each treatment in the Tunggul sandy loam soil ranged from 27.4 to 89.7 and 6.27 to 19.1 $\mu\text{g N m}^{-2} \text{h}^{-1}$ in the wet and dry seasons, respectively. The mean of the N₂O 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 $\mu\text{g N m}^{-2} \text{h}^{-1}$ 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 Tungal soil, coated fertilizer reduced N₂O emissions by 31 and 48% in wet and dry seasons, respectively, compared to the conventional fertilizer, and was similar to unfertilized treatment. However, N₂O emissions increased in Simunjan and Tatau soils during dry seasons. There was no significant difference between treatments. These results show that N₂O and CO₂ 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, N₂O and CO₂ fluxes, sandy loam, sandy, peat soil.

INTRODUCTION

Carbon dioxide (CO₂) and nitrous oxide (N₂O) account for 77 and 7.9% of the total anthropogenic greenhouse gas (GHG) emissions, respectively, at different values of global warming potentials (Rogner

et al. 2007). Agricultural soils act as both a source and a sink for carbon and nitrogen (N) gases (Bouwman *et al.* 1995). From a greenhouse gas perspective, the fertilizers with the largest effects are the N-based forms that produce N₂O, including ammonium nitrate, ammonium sulphate and urea. According to the Intergovernmental Panel on Climate Change (IPCC), 1 kg of N₂O has an equivalent impact of approximately 298 kg of CO₂. N₂O is responsible for 7.5% of the calculated greenhouse effect caused by human activity. The concentration of N₂O in the

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atmosphere is increasing at a rate of approximately 0.2% per year (IPCC 2007).

N₂O is produced by both the oxidation of ammonium (NH₄⁺) to nitrate (NO₃⁻) (i.e., nitrification) and the reduction of NO₃⁻ to dinitrogen gas (N₂) (i.e., denitrification). N₂O 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, N₂O emissions from agricultural soils are particularly large, and obtaining reliable estimates is not straightforward (Sylväsalo *et al.* 2004). The amount of N₂O released is usually related to N application as organic or mineral fertilizers; a linear relationship between N₂O 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).

The emission factor (EF, i.e., the ratio of N₂O-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.

Oil palm (*Elaeis guineensis* Jacq) production in Indonesia and Malaysia is currently the focus of debates due to its potential impact on the environment when tropical rain forests are converted into such plantations (Dewi *et al.* 2009). Oil palm plantations have been reported to release large quantities of N₂O 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 N₂O 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). 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 CO₂ into the atmosphere.

Soils in tropical ecosystems emit far more N₂O than soils in other terrestrial ecosystems (Sanhueza *et al.* 1990). Because of the variability in soil types and soil moisture fluxes, some tropical soils emit more N₂O 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 N₂O 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 type with N fertilizer, in relation to N₂O and CO₂ emission rates, are still limited. Coated fertilizer is one of fertilizer forms that has been reported to reduce N₂O emission rate by effectively controlling the release of NH₄⁺, which caused a prolonged production period of NO₃⁻ 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 NO₃⁻ concentration would be expected to limit denitrification, providing an explanation for the low N₂O 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, we evaluated the emissions of the greenhouse gases N₂O and CO₂ from oil palm plantation fields in Indonesia and Malaysia, across three types of soil (sandy, sandy loam and peat soil) in response to treatments of N fertilizer application.

MATERIALS AND METHODS

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. 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 M: coated fertilizer in granular form was applied by the deep placement method: namely, after

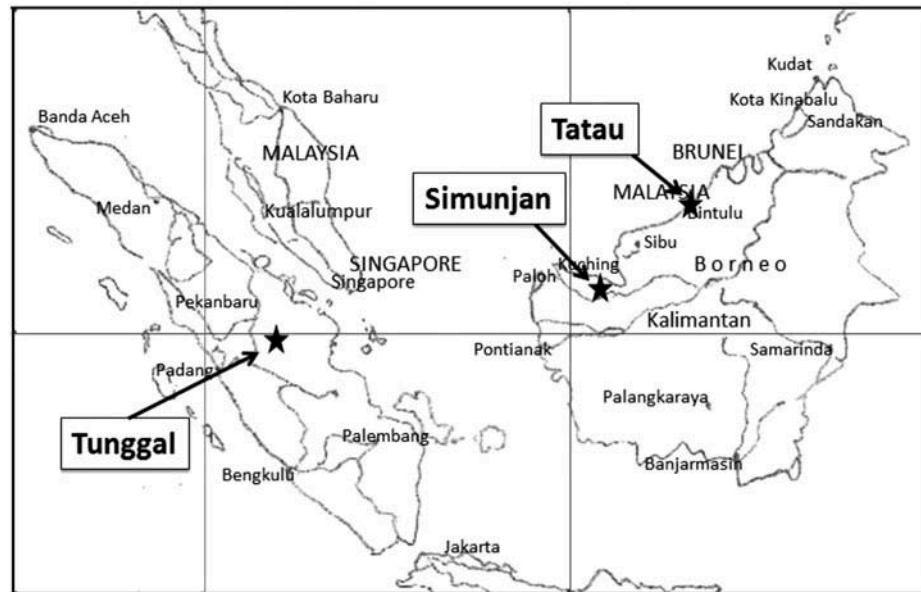


Figure 1 Map of study sites in Indonesia and Malaysia.

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.

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

Treatment B2: no nitrogen fertilizer, with tillage only in the soil (0–15 cm) in a similar way as in treatment M.

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. 2a–c, 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

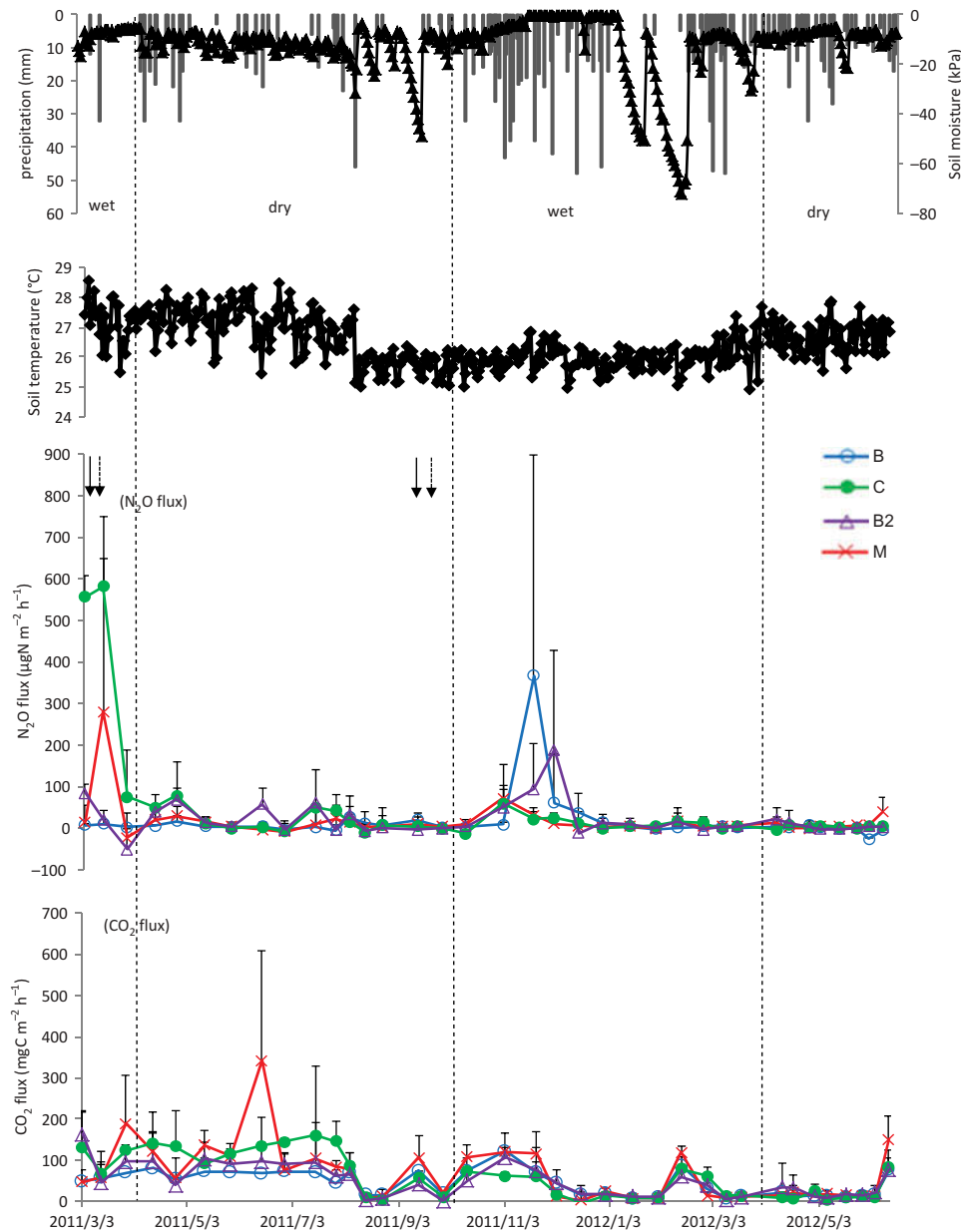


Figure 2a Precipitation, soil moisture tension, soil temperature, nitrous oxide (N₂O) flux and carbon dioxide (CO₂) flux in Tunggul sandy loam soil. Vertical bars indicate \pm standard deviation. Treatment B: no nitrogen (N) fertilizer and no tillage; C: conventional fertilizer; B2: no N fertilizer with 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.

method (Anderson and Ingram 1989) and hydrazine reduction method (Hayashi *et al.* 1997), respectively.

Soil moisture was measured 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). 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.

Measurement of N₂O and CO₂ fluxes

Measurement of N₂O and CO₂ fluxes was conducted at 2-week intervals over a period of 15 months from

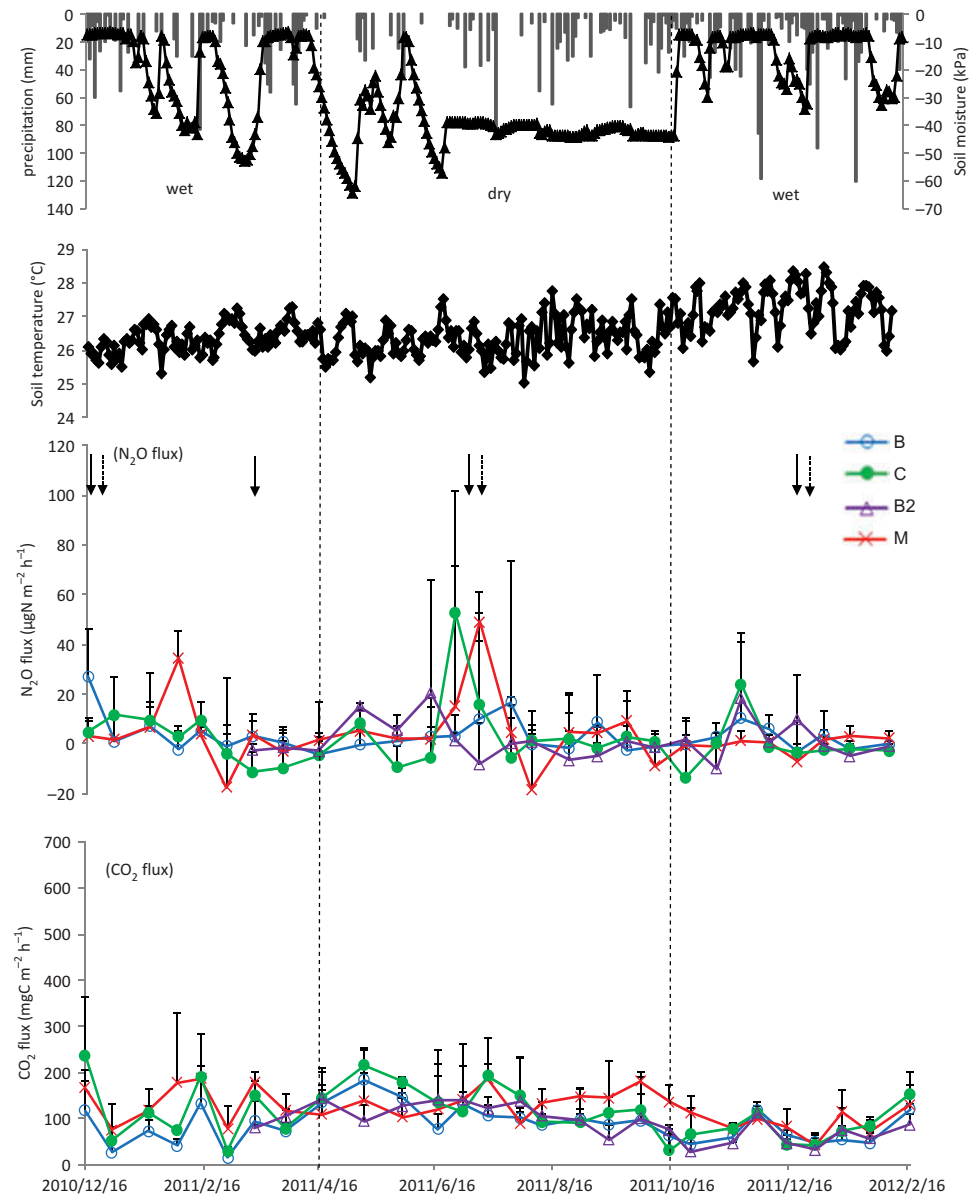


Figure 2b Precipitation, soil moisture tension, soil temperature, N₂O flux, and CO₂ flux, in Simunjan sandy soil. See details for other remarks in Fig. 2a.

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. N₂O and CO₂ 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 N₂O and CO₂ fluxes were measured by a gas chromatograph (GC-14B, Shimadzu, Japan) equipped with an electron capture detector (ECD) and thermal detector

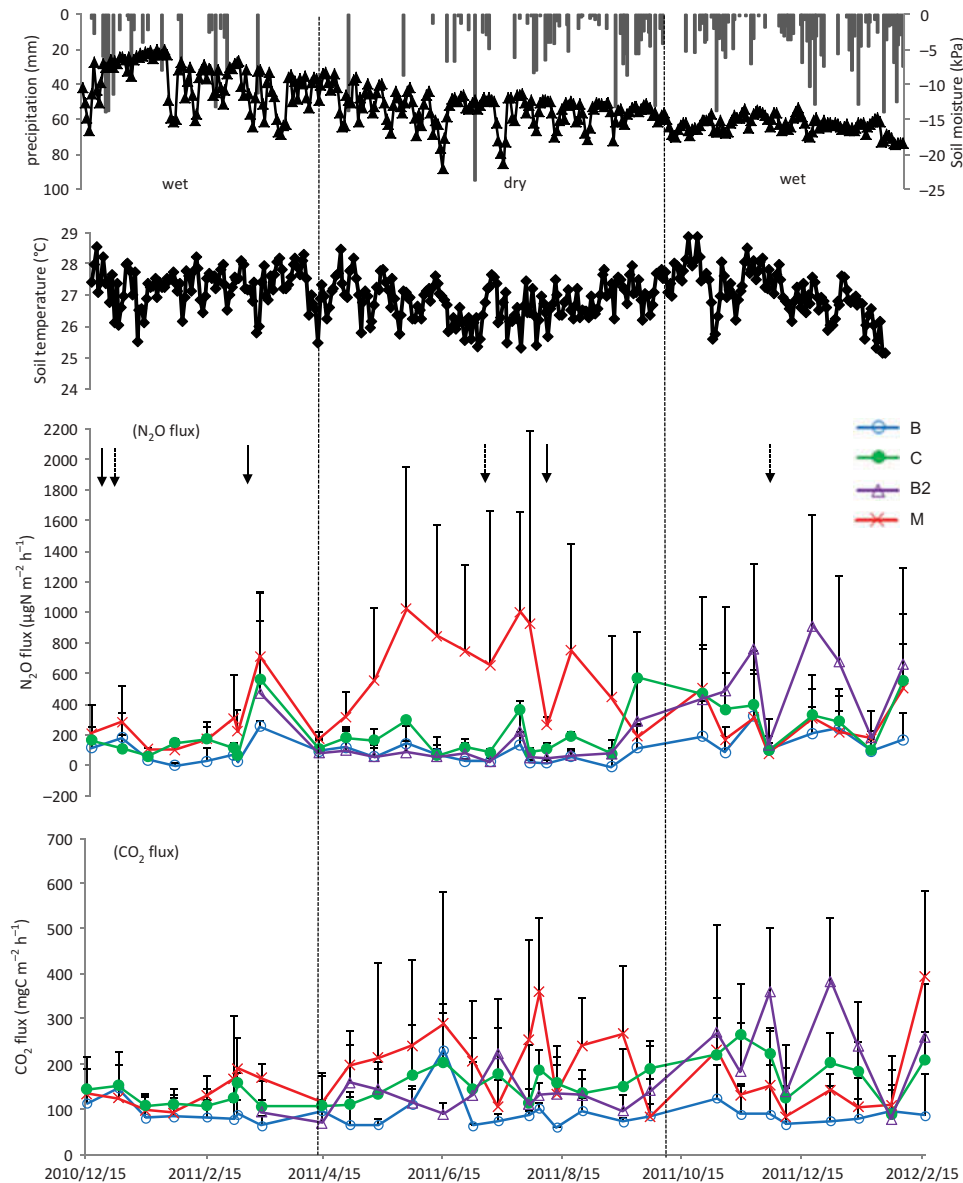


Figure 2c Precipitation, soil moisture tension, soil temperature, N₂O flux, and CO₂ flux, in Tatau peat soil. See details for other remarks in Fig. 2a.

(TCD), respectively. The emission factor (EF) was calculated using cumulative N₂O fluxes to determine the percentage of N₂O-N emitted for each fertilizer treatment (Dobbie and Smith 2003; Jumadi *et al.* 2008). The emission factor (EF) was calculated using the following formula:

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

where M and C are the cumulative N₂O fluxes emitted from coated fertilizer and conventional fertilizer

treatment (kg N₂O-N ha⁻¹ period⁻¹), respectively; B2 and B are the cumulative cumulative N₂O fluxes (kg N₂O-N ha⁻¹ period⁻¹) emitted from non-N fertilizer treatment with and without tillage, respectively.

Statistical analysis

The significance of the cumulative N₂O and CO₂ fluxes for each treatment and study site were analysed using a two-way analysis of variance (ANOVA) test. Means of N₂O and CO₂ 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.

RESULTS

Physicochemical soil properties of study sites

The physicochemical properties of the three soil types were varied (Table 1). In Tunggul and Simunjan, both were mineral soils with different particle size distributions. Sand content was higher in Simunjan than in Tunggul, while clay and silt contents were higher in Tunggul 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 and emission factors

N_2O fluxes for Tunggul, Simunjan and Tatau are shown in Fig. 2a, b and c respectively. In Tunggul sandy loam soil, it was observed that there were high N_2O fluxes ($279\text{--}581 \mu\text{g N m}^{-2} \text{h}^{-1}$) 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. 2a). In the Simunjan sandy soil, N_2O fluxes were

lower (up to $52.5 \mu\text{g N m}^{-2} \text{h}^{-1}$) than in the Tunggul sandy loam soil, but peaks were observed after heavy rains not only in the wet season, but also in the dry season (Fig. 2b). N_2O fluxes in the Tatau peat soil were higher and more variable (up to $1022 \mu\text{g N m}^{-2} \text{h}^{-1}$) 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. 2c).

During the study period, N_2O fluxes varied across all study sites and treatments (Table 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 $5.34 \mu\text{g N m}^{-2} \text{h}^{-1}$ in the wet and dry seasons, respectively. The mean of N_2O fluxes in the Tunggul sandy loam soil ranged from 27.4 to 89.7 and 6.27 to $19.1 \mu\text{g N m}^{-2} \text{h}^{-1}$ 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 $606 \mu\text{g N m}^{-2} \text{h}^{-1}$ 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 equalled the unfertilized treatment only in the Tunggul 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 ($p = 0.000$) and combination factor of sites, treatments and seasons ($p = 0.020$) (Table 2).

The cumulative N_2O fluxes are summarized in Table 3. Cumulative N_2O fluxes ranged from 0.59 to

Table 1 Descriptions and physicochemical characteristics of soils at the oil palm plantation study sites

Description	Study sites		
	Tunggul	Simunjan	Tatau
Soil type	Sandy loam (62% sand, 5% clay, 33% silt)	Sandy (97% sand, 0.03% clay, 2.97% silt)	Peat
Total area (ha)	14,000	7900	9000
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 Nitrous oxide (N₂O) fluxes for the three study sites during wet and dry seasons

Study sites	Treatments	N ₂ O 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
Simunjan	M	28.2 ± 36.0	8.30 ± 5.87
	B	3.81 ± 1.42	2.40 ± 4.79
	B2	0.80 ± 3.65	1.63 ± 1.12
Tatau	C	1.60 ± 1.57	3.20 ± 2.51
	M	2.18 ± 2.73	5.34 ± 7.03
	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 × treatments	6	2.449	0.038
Sites × seasons	2	0.303	0.740
Treatments × seasons	3	2.755	0.053
Sites × treatments × 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.

4.09, 0.11 to 0.42 and 11.1 to 42.7 kg N ha⁻¹ period⁻¹, in Tunggal sandy loam soil, Simujan sandy soil and Tatau peat soil, respectively. Results indicated the highest cumulative N₂O fluxes in the Tatau peat soil and the lowest cumulative N₂O fluxes in Simunjan sandy soil. Two-way ANOVA analysis determined that there were statistically significant differences in cumulative N₂O fluxes among the study sites ($p = 0.000$), though no

Table 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 × 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.

significant difference was found in the treatments within each study site ($p = 0.125$) (Table 3).

Among the three study sites, the N₂O 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 4).

EF for the conventional and coated fertilizer applications showed significantly positive correlation with the soil parameters such as NO₃⁻, NH₄⁺, total N, total carbon and WFPS, and has a significantly negative correlation with the soil pH and BD (Table 5).

Soil CO₂ emission

CO₂ fluxes are presented in Fig. 2a, b and c for Tunggal, Simunjan and Tatau, respectively. During the study period, CO₂ fluxes varied across all the study sites and treatments (Table 6). The mean of the CO₂ fluxes in the Tunggal sandy loam soil ranged from 45.5 to 56.8 and 56.4 to 96.5 mg carbon m⁻² h⁻¹ in wet and dry seasons,

Table 3 Cumulative nitrous oxide (N₂O) fluxes for the three study sites

Study sites	Cumulative N ₂ O 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 × 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 5 Pearson correlation of nitrous oxide (N₂O) emission factors (EF) between the conventional fertilizer and the coated fertilizer among soil parameters for the three study sites (*n* = 9)

Soil Parameters	N ₂ O EF (%)	
	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 (NO₃⁻); ammonium (NH₄⁺); total nitrogen (Total N); total carbon (Total C); bulk density (BD); water-filled pore space (WFPS).

respectively. The mean of the CO₂ fluxes in the Simunjan sandy soil ranged from 71.1 to 114 and 104 to 134 mg carbon m⁻² h⁻¹ in wet and dry seasons, respectively. The mean of the CO₂ fluxes was found to be highest in the Tatau peat soil, ranging from 89.8 to 223 and 92.7 to 208 mg carbon 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 CO₂ fluxes by effect of study sites only (*p* = 0.000) (Table 6). In Tatau peat soil, as the soil temperature decreased, the soil CO₂ fluxes tended to increase. However, these CO₂ fluxes included both soil and root respiration, but these values might be underestimated due to relatively long closure time, as 20 minutes.

Cumulative CO₂ fluxes ranged from 5302 to 7971, 7638 to 11431 and 8797 to 16949 kg carbon ha⁻¹ period⁻¹, in Tunggal sandy loam, Simunjan sandy soil and Tatau peat, respectively (Table 7). Among the three study sites, the cumulative CO₂ fluxes were highest in the Tatau peat soil and lowest in the Tunggal sandy loam soil. For cumulative CO₂ 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).

Table 7 Cumulative carbon dioxide (CO₂) fluxes for the three study sites

Study sites	Cumulative CO ₂ fluxes (kg carbon 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	<i>df</i>	<i>F</i> value	<i>p</i> value	
Sites	2	13.62	0.000	
Treatments	3	3.094	0.064	
Sites × 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.

Table 6 Carbon dioxide (CO₂) fluxes for the three study sites during the wet and dry seasons

Study sites	Treatments	CO ₂ flux (mg carbon 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
Simunjan	M	56.8 ± 15.3	96.5 ± 15.1
	B	72.1 ± 10.9	104 ± 8.55
	B2	71.1 ± 3.66	134 ± 34.5
Tatau	C	101 ± 14.0	126 ± 10.2
	M	114 ± 7.93	105 ± 46.5
	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	<i>df</i>	<i>F</i> value	<i>p</i> value
Sites	2	34.525	0.000
Treatments	3	4.287	0.059
Seasons	1	1.576	0.215
Sites × treatments	6	1.608	0.165
Sites × seasons	2	2.179	0.124
Treatments × seasons	3	1.051	0.379
Sites × treatments × 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.

DISCUSSION

N₂O fluxes and EF correlated with soil and fertilizer types

In Tunggal sandy loam soil, the highest N₂O fluxes were measured in the wet season, March 2011 (Fig. 2a). High peaks of N₂O 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 N₂O fluxes after N fertilization are not unusual and often show a marked response to precipitation events. The results also showed that N₂O fluxes increased after N fertilization, reached a peak, then decreased rapidly before levelling off after approximately 1 to 2 weeks. Subsequently, N₂O fluxes gradually decreased before sharply increasing again in December 2011 with both high precipitation and soil moisture.

In Simunjan sandy soil, high N₂O fluxes were shown twice in the wet season and one time in the dry season when precipitation was high (Fig. 2b). 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 N₂O out of the soil (Inubushi *et al.* 1996). During the study period, there were negative N₂O emissions that may be explained by a decrease in gas diffusivity, leading to increased microbial consumption of N₂O and denitrification before emission (Arah *et al.* 1991). Although production rates of N₂O are usually larger than consumption rates, stressed soils that are usually considered as net sources of atmospheric N₂O can temporarily become a sink (Minami 1997; Inubushi *et al.* 2003).

In Tatau peat soil, fluxes of N₂O were higher than those in sandy loam and sandy soils. Although the pattern of N₂O fluxes varied during the study period, the coated fertilizer application remained high throughout the study period (Fig. 2c). N₂O emissions were particularly high when fertilizer was applied to wet peat soil. N₂O 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 N₂O fluxes is generally relative to the rates of denitrification affected by moisture content and the quantities of NO₃⁻, NH₄⁺ and carbon substrates in soil (Clayton *et al.* 1994; Couwenberg 2009).

In our study, patterns of N₂O emissions were affected by type of soil, precipitation and soil moisture. Freshly wetted soils often have 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 it 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 CO₂ flux. High N₂O fluxes in peat soils are further correlated significantly with denitrification activity where a high content of NO₃⁻, NH₄⁺ and WFPS are present in the soil. Large amounts of NH₄⁺ and NO₃⁻ 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 N₂O.

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 N₂O reductase to proton activity, and it is also likely that all denitrifying enzymes are susceptible at low soil pH and produce N₂O from other intermediate products (Nägele and Conrad 1990).

In our study, coated fertilizer reduced N₂O emission in Tunggul sandy loam soil. However, coated fertilizer exhibited higher N₂O emission compared to conventional fertilizer in Simunjan sandy soil and Tatau peat. Delgado and Mosier (1996) observed similar results in which N₂O 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 N₂O emission mitigation depends on increases in the nitrification-derived N₂O 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 N₂O 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).

The emission factors are highest for Tatau peat soil compared with Tunggul 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 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.* 2008). Therefore, these EF values are

mostly dependent on management practices, fertilizer types, climate and soil types.

CO₂ fluxes correlated with soil types

Soil CO₂ 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 CO₂ flux vary by ecosystem (Raich and Schlesinger 1992; Melling *et al.* 2005). In our study, the soil CO₂ fluxes were not directly influenced by soil temperature. In the Tatau peat soil, as the soil temperature decreased, the soil CO₂ 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 CO₂ fluxes. In the other two mineral soils, the CO₂ fluxes tended to be higher in the Simunjan sandy soil than in the Tungal sandy loam soil. In the Tatau peat soil, CO₂ fluxes were highest among three soils examined which may be due to higher soil carbon content. The relationship between quantity of soil carbon, soil CO₂ flux and litter respiration remains a serious concern (Gu *et al.* 2004). The rate of CO₂ transmission from soils to the atmosphere is determined by microbial respiration, root respiration and bulk soil respiration and is predominantly regulated by soil microorganisms found within the soil organic matter (Raich and Schlesinger 1992).

CONCLUSION

The effect of soil types on N₂O and CO₂ fluxes in the studied tropical oil palm plantation was highly significant, but no consistent tendency was observed using different N fertilizers. N₂O and CO₂ fluxes showed high variation with soil types, N fertilizer and seasons. N₂O fluxes were highest in the Tatau peat soil, followed by the Tungal sandy loam soil and the Simunjan sandy soil, respectively. 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 N₂O and CO₂ fluxes in oil palm plantations.

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