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Influence of soil aggregate size on greenhouse gas emission and uptake rate from tropical peat soil in forest and different oil palm development years

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ABSTRACT

The influence of oil palm development on tropical peat soil decomposition rate was investigated by an incubation experiment. Soil samples from soil surface and around underground water table were taken from forest site, and oil palm site at 1st and 9th year after development. The soil samples were sieved into 0–2 mm, 2–8 mm and 8–20 mm and analyzed for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) fluxes.
The development of oil palm did not change the CO_2 emissions and showed inconsistent influence on CH_4 flux according to aggregate size, while significantly higher N_2O emissions were found for aggregates 0–2 mm at high moisture of oil palm plantation soils compared with the original forest. Nitrous oxide fluxes showed significant positive correlation with the CO_2 flux, which indicated that soil organic matter decomposition was closely related to the N_2O production. On the other hand, CH_4 flux showed clear emission for aggregates bigger than 2 mm, while aggregates size 0–2 mm showed consistent CH_4 uptake. These results showed that investigation of greenhouse gas emissions in tropical peat soil must take into account the aggregate characteristics of the soil, which are inhomogeneous and mixed with fresh organic matter.

1. Introduction

Tropical peat soil constitutes over 8% (33–49 M ha) of the global peat soils (Maltby and Immirzi, 1993). Of this, 60–70% of the tropical peat soils are found in south-east Asia, mainly in Indonesia and Malaysia (Maltby and Immirzi, 1993). Recently, in Sarawak, Malaysia, areas planted with oil palms expanded from just 14091 ha in 1975 to 839748 ha in 2009 (Department of Statistics Malaysia, 2011), with half of those on tropical peat soil. The peat soils in Borneo Ireland were developed under high underground water table and the thickness of peat can reach 20 m in depth (Page et al. 1999). Due to the deeper underground water table required for oil palm growth, drainages are built in the peat soils that lead to dryer soil condition.

Conversion of tropical peat land into oil palm plantations receives global attention about the greenhouse gas emissions (Miettinen et al., 2011). The measurements in the fields, however, show inconsistent results. In some studies, the peat soil decomposition shows extremely high greenhouse gas emissions due to cultivation (Takakai et al., 2006), while other studies report of lower emissions in oil palm plantations compared to natural forests (Melling et al., 2005). The dominant controlling factors in soil respiration for example were relative humidity for forest while proportion of water filled pore space for oil palms (Melling et al., 2005). These factors are influenced by the management methods in and around the oil palm plantation. Degraded peat soils showed higher carbon (C) turnover and increased dissolved organic C release, while dissolved organic nitrogen (N) release was independent of it, indicating the strong influence of management practices such as fertilization on the N pool (Kalbitz and Geyer, 2002). Common condition must be created and compared in the laboratory to analyze whether the condition of peat soil itself has also changed or just the surrounding condition has changed.

Thus, the objective of this study was to analyze the influence of oil palm development on the peat soil decomposition rate at aggregate scale. To clarify this effect, soils from different depths and aggregate sizes were also investigated in the laboratory.

2. Materials and methods

The study site was an oil palm plantation near Sibu, Sarawak, Malaysia (N 2° 9′, E 111° 53′). The plantation area has been constantly developing from 2000 with an approximate area of 10000 ha in 2009. A small part of natural forest (1% of the whole area) was left at the edge of the plantation. Soil samples were taken from the forest site and oil palm plots developed in 2000 (9th year after development) and in 2008 (1st year after development) on 9th July 2009. The types of peat (previous forest types in oil palm fields) were peat swamp forest for all three sites. Mixed peat swamp forest has an uneven canopy with a mean canopy height of about 21 m in which its emergent can reach a

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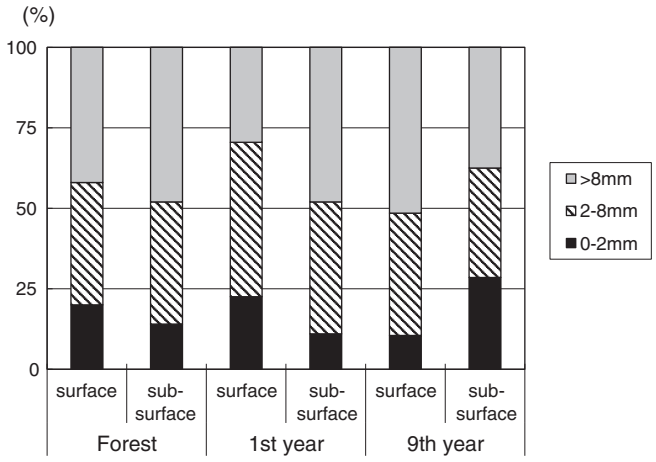

Fig. 1. Proportion of different aggregate size of surface and sub-surface soil of forest, 1st year and 9th year after development.

height of 40 m. Forest compositions includes principle species such as Ramin (*Gonstylus bancanus (Miq.) Kurz*), Alan (*Shorea albida*), Jongkong (*Dactylocladus stenostachys*) and Kapur (*Drybalanops rappa*). From each site, composite soil samples of 5 points were taken from the surface at 0–10 cm depth and sub-surface around underground water table. The underground water table depth of the forest was 70 cm whereas the 1st year site was 80 cm and 9th year site 30 cm. The soil was air dried for 2 days at ambient temperature (20–25 °C) to adjust the water content since the initial moisture content varied from 40 to 81% at wet weight basis at initial condition. The average water filled pore space (WFPS) was 74.2% for the surface 0–10 cm of the forest site, thus its air filled pore space (AFPS) was 25.8%. The WFPS and AFPS were 64.5% and 35.5% for the surface of the 1st year, and .83.6% and 16.4% for the surface of the 9th year oil palm plantation, respectively. The aggregates were separated into aggregate sizes of 0–2 mm, 2–8 mm and 8–20 mm according to Kristiansen et al. (2006). Each aggregate fraction was investigated for its pH using a portable pH meter equipped with combined electrode (pH/ION METER D-23, Horiba, Japan), carbon and nitrogen content by NC analyzer (SUMIGRAPH NC-80, Sumitomo Chemical Co., Japan), nitrate content by ion chromatography (CT0-20AC, Shimazu Co., Japan) and ammonium content by indophenole method (UV-160, Shimazu Co., Japan).

5 g DW of each aggregate size was put in an incubation bottle (100 ml) equipped with a pressure bag. The soil moisture was adjusted to two levels of 30% and 70% at wet weight basis to simulate the dried and drained condition, respectively. Four replications were made for each treatment. All samples were incubated at 30 °C for 21 days. The soil moisture content was adjusted every second day to the initial condition of 30% and 70% for each treatment. The incubation was separated into 2 phases with each phase comprising 2 replications from each treatment. The second phase started 1 day after the first.

Gas samples incubation was conducted during 0–1st, 1st–2nd, 6th–7th, 7th–8th, 13th–14th and 20th–21st day after incubation start. The incubation bottle was sealed with ambient air and gas samples were taken before and after the incubation. Gas samples were put into a vacuum vial and analyzed for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) concentration using TCD-GC (GC-8A, Shimazu Co., Japan), FID-GC (GC-8A, Shimazu Co., Japan) and ECD-GC (GC-2014, Shimazu Co., Japan), respectively. The difference of gas concentrations before and after the incubation of 24 h was converted into gas emission/uptake rate per soil dry weight.

Statistical analysis was conducted using SimgaPlot12.0 (Systat Software Inc). One way analysis of variance on rank by Turkey was conducted to compare pairwise all treatments. Peason's correlation test was conducted to compare the relation of different gas emission/uptake rate of different aggregate size.

3. Results

3.1. Initial characteristics of the investigated aggregates

The proportions of sieved aggregate sizes showed insignificant difference among the investigated sites (Fig. 1). However, the average proportion of aggregate size, 0–2 mm, over all sites and depths at 17.8% was much lower than 2–8 mm and 8–20 mm. The last two had average proportions of 29.5 and 42.8%, respectively. The proportion less than 2 mm was significantly ($p<0.001$) lower than 2–8 mm and 8–20 mm, while the proportion of 2–8 mm and 8–20 mm did not differ. The basic characteristics of 2–8 mm and 8–20 mm were not significantly different, so only the characteristics of 0–2 mm and 2–8 mm from different land uses and depth are shown in Table 1. The pH of the soil ranged from 3.6 to 4.1 showing no significant difference among land uses, depth and aggregate sizes (Table 1). Total C did not differ among land uses, depths and aggregate sizes, but total N was higher in aggregates size 0–2 mm compared to 2–8 mm. Thus, CN ratio became smaller in aggregate size 0–2 mm than 2–8 mm. Nitrate and ammonium was significantly higher in forest than in oil palms. They were also significantly higher in the surface soils compared with sub-surface soils.

3.2. Greenhouse gas emission/uptake rate from different aggregate sizes

The emission/uptake rates were higher at the beginning of the incubation and got lower toward the end of the incubation. As for the forest soils, the final cumulative emission rates of CO_2 of surface and sub-surface soils showed different tendency according to depth and soil moisture (Fig. 2a). There was no clear tendency among cumulative emission rates of CO_2 according to different aggregate sizes for surface soil, but for sub-surface soil CO_2 emission rates tended to increase as

Table 1
Characteristics of different aggregates from different land uses and depths.

			pH	Total C (g kg^{-1})	Total N (g kg^{-1})	CN ratio	Nitrate (mg N kg^{-1})	Ammonium (mg N kg^{-1})
Forest	Surface	0–2 mm	3.8	564	23 ab	24.6 b	68.6 a	15.7 a
		2–8 mm	3.9	583	19 b	30.8 b	71.8 a	9.7 ab
	Sub-surface	0–2 mm	4.1	561	35 a	15.9 c	37.1 b	6.4 bc
		2–8 mm	3.7	550	19 b	28.8 b	30.9 b	3.8 de
1st year	Surface	0–2 mm	3.9	566	21 b	26.8 b	24.7 bc	5.3 c
		2–8 mm	4.2	590	19 b	31.0 b	25.0 bc	4.2 cd
	Sub-surface	0–2 mm	3.6	555	22 b	25.3 b	2.4 d	0.9 e
		2–8 mm	3.9	563	18 b	30.8 b	2.3 d	0.7 e
9th year	Surface	0–2 mm	3.8	533	20 b	26.2 b	21.1 c	1.1 e
		2–8 mm	3.6	572	15 c	37.1 a	19.5 c	1.1 e
	Sub-surface	0–2 mm	4.0	527	23 ab	22.9 b	8.6 e	0.1 f
		2–8 mm	3.9	523	12 c	43.1 a	8.4 e	0.1 f

Different letter indicate significant difference by Turkey test ($p<0.05$).

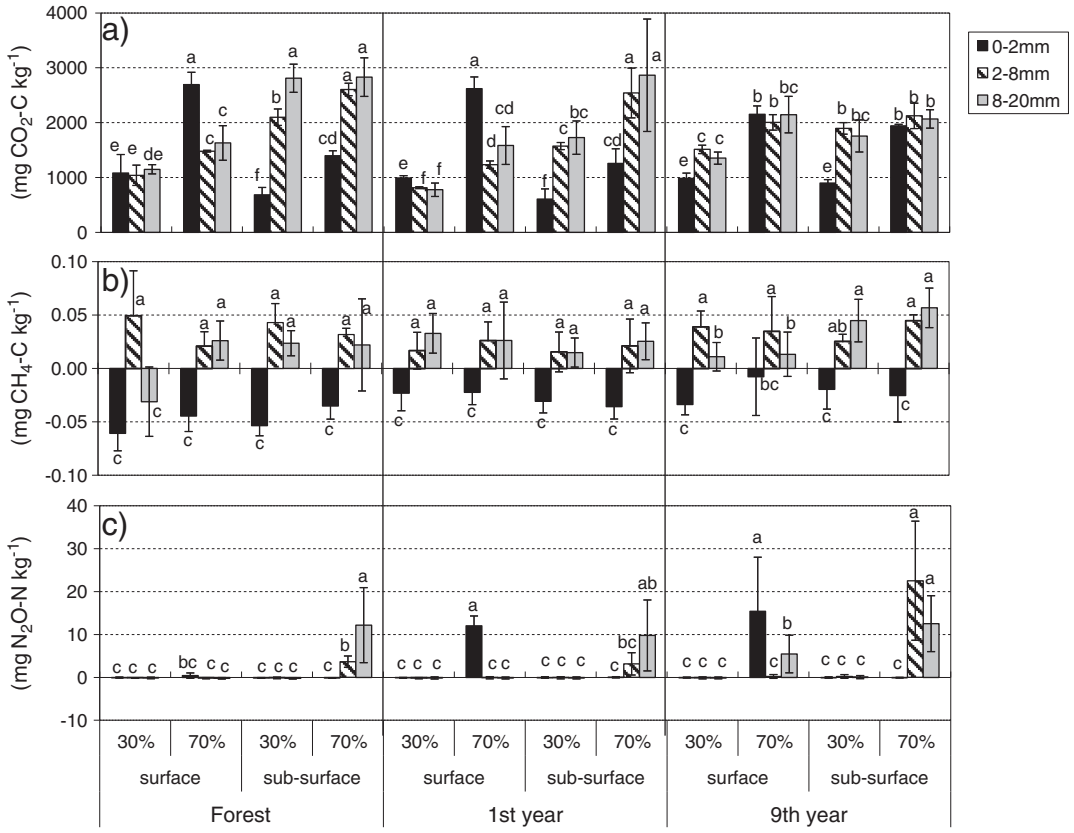

Fig. 2. Cumulative amount for 21 days of a) CO2, b) CH4 and c) N2O flux of forest, 1st year and 9th year oil palm soil according to different depth and soil moisture. Different letter indicate significant difference by Turkey Test ($p<0.05$), error bar indicates the standard deviation ($n=4$).

aggregate size increase. The treatment with 70% soil moisture was significantly higher than those with 30%, especially for 0–2 mm. For sub-surface soils, bigger aggregate size showed higher CO_2 emission rates than smaller size at both soil moisture treatments. The aggregate size 0–2 mm of sub-surface soil with 30% soil moisture was 686 mg CO_2–C kg^{-1} and was lowest among all treatments. The aggregate size 8–20 mm of sub-surface soil with 70% soil moisture was 2830 mg CO_2–C kg^{-1} and was the highest among all treatments. Comparing the same aggregate size between soil depths, the aggregate size 0–2 mm of surface soil showed higher CO_2 emission rates than sub-surface soil, while aggregate size bigger than 2 mm showed higher CO_2 emission rates for sub-surface soils. Similar influence of depth, soil moisture and aggregate sizes on CO_2 emission was found for the 1st year oil palm soils, while the 9th year showed no clear tendency.

The cumulative emission/uptake rates of CH_4 showed no significant difference among soil depths and soil moistures (Fig. 2b). While aggregate size of 0–2 mm showed uptake, bigger aggregate size showed emission rates for all land uses except for 8–20 mm aggregate size of surface soil with 30% soil moisture of forest soil.

The cumulative emission rates of N_2O showed both negative and positive values (Fig. 2c). Significantly larger emissions were only found for 70% soil moisture. The emission from aggregate size 8–20 mm of sub-surface soil of the 9th year oil palm with 70% soil moisture showed the highest emission rate with 22.5 mg N_2O–N kg^{-1}.

3.3. Correlation of greenhouse gas emission/uptake rates in relation to land use and aggregate size

To investigate the change in greenhouse gas emission/uptake rates due to oil palm development, the cumulative greenhouse gas emission/uptake rates of oil palms of Fig. 2 were compared to that of forest according to each aggregate sizes and sites (Fig. 3). The effects of soil depth and water treatment were not differentiated in this figure. The relationship between cumulative emission rates of CO_2 at forest site and oil palm plantation sites was closely scattered along the 1:1 line (Fig. 3a). The emission rate of the 1st year development tended to be lower than the 1:1 line, while the emission rate of the 9th year development tended to show a wider deviation from the 1:1 line. The CH_4 at oil palm plantation site showed cumulative uptake rates for aggregate size 0–2 mm and emission rates for bigger aggregate sizes as illustrated by the forest site (Fig. 3b). The uptake for aggregate size 0–2 mm was smaller at the oil palm plantation sites than the forest site. The emission rate for aggregate size bigger than 2 mm of the 1st year development was smaller than the forest site, while 9th year development tended to be bigger than the forest site. The cumulative emission rates of N_2O at oil palm sites showed four points that were higher than the forest site (Fig. 3c). Those four points were incubated at 70% soil moisture. The highest point was 9th year development with aggregate size of 2–8 mm with a cumulative emission rates of 23.5 mg N_2O–N kg^{-1}. The second highest was 9th year development with 0–2 mm aggregate size, followed by the 1st year development with 0–2 mm size.

As the correlation of cumulative CO_2, CH_4 and N_2O gas emission/uptake rates of different aggregate sizes were compared with each other, only the CO_2 and N_2O emission rates showed positive correlation with each other within the same aggregate size (Table 2). The relation was especially high for the aggregate size 0–2 mm ($p<0.001$). The relation for the aggregate size 2–8 mm was not significant at $p<0.05$ but at $p<0.1$. Among the different aggregate sizes, there was no correlation between aggregate size 0–2 mm and the bigger aggregates. However, positive correlation was found between aggregate size 2–8 mm and 8–20 mm. The CO_2 and N_2O emission rates of both aggregate sizes showed highly significant correlation. In addition, the CO_2 emission rates of aggregate size 2–8 mm showed also significant

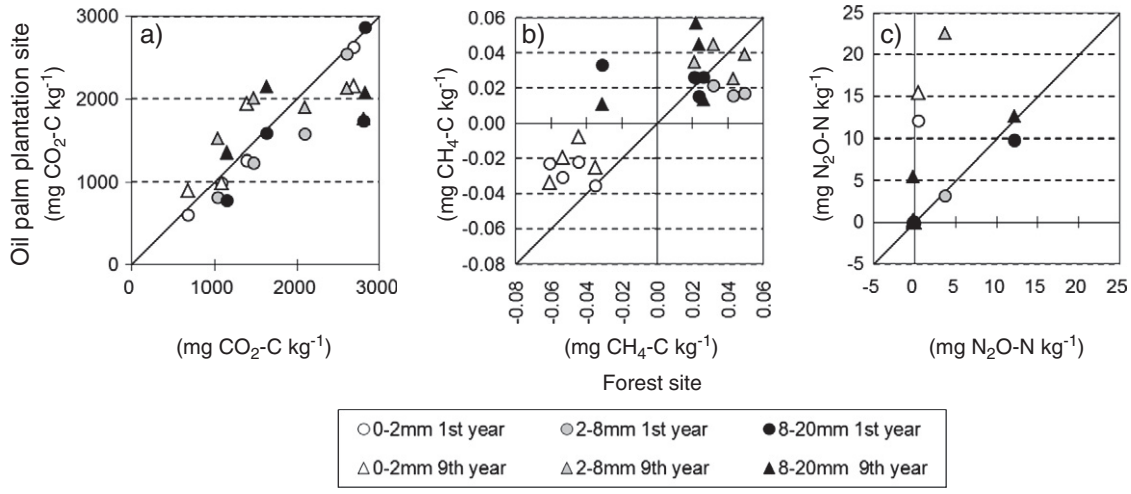

Fig. 3. Relation of the cumulative a) CO_2, b) CH_4 and c) N_2O flux from different aggregate size at forest site and oil palm plantation site of different development years. The line indicate the 1:1 relation between the flux at forest site and oil plantation site.Different soil depth and water treatments are not distinguished.

correlation to the N_2O emission rates of aggregate size 8–20 mm. The cumulative CH_4 emission/uptake rates showed no relation to CO_2 or N_2O emission rates.

As the characteristics of aggregates were compared to the cumulative gas emission/uptake rates, only CH_4 showed significant relations. It showed negative correlation to soil total N ($r=-0.71$, $p<0.001$) and positive correlation to CN ratio ($r=0.77$, $p<0.001$).

4. Discussion

4.1. Influence of aggregate size on greenhouse gas emission/uptake rates

The CO_2, CH_4 and N_2O gas emission/uptake rates showed different trends according to the aggregate size (Fig. 2). For CO_2 emission rates, aggregates of 0–2 mm showed lower emission than aggregates bigger than 2 mm except for surface soils at 70% soil moisture. The aggregate structure plays an important role in the accessibility of soil organic matter (SOM) for microbial decomposition (Jastrow et al., 2007). Microaggregates (250 mm diameter) formed by primary particles coupled together by plant and microbial debris and by humic materials or polysaccharide polymers better protect SOM against decomposition than do macroaggregates (4250 mm diameter) (Denef et al., 2001). On the other hand, there are several reports showing inconsistent relationships between soil aggregate sizes and greenhouse gas production due to 1) differences in soil microbial community, 2) differences in nutrient content and 3) measurement methods (Sey et al., 2008).

In this study, tropical peat soil with low pH and different land uses were investigated. The results showed that high CO_2 emission rates of 0–2 mm surface soils at 70% soil moisture was found for all land uses (Figs. 2a and 3a). Fresh organic matter accumulates at the surface of peat soil. While bigger aggregates contained more fresh organic materials, smaller aggregate contained more broken down organic matter, making its availability easier to microorganisms. This contention was supported by the lower CN ratio for aggregate size 0–2 mm compared with 2–8 mm (Table 1). The water content of 30% was obviously too dry for microorganisms, leading to higher CO_2 emission rates at 70% soil moisture. At sub-surface, high CO_2 emission was found for bigger aggregates, even though its CN ratio was significantly lower than the smaller aggregate size of 0–2 mm (Table 1). Easily decomposable small organic particles may have disappeared during the formation of the deeper layers, leaving the bigger aggregates more susceptible to decomposition. The total C did not differ significantly between land uses, depth or aggregate sizes. More detailed analysis of available C must be conducted to detect the difference in available C to explain the difference among aggregates.

4.2. Influence of oil palm development on greenhouse gas emission/uptake rates

The influence of oil palm development on CO_2 emission was found most pronounced for the 9th year development, showing more deviation of from the 1:1 line (Fig. 3a). The proportion of aggregate

Table 2
Correlation of cumulative CO_2, CH_4 and N_2O gas fluxes at different aggregate sizes.

		0–2 mm			2–8 mm			8–20 mm		
		CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
0–2 mm	CO_2		0.18	0.51***	−0.02	−0.03	0.17	−0.04	0.15	0.17
	CH_4			0.14	0.01	−0.20	0.22	0.02	0.22	0.19
	N_2O				−0.03	−0.05	−0.12	0.01	−0.13	−0.02
2–8 mm	CO_2					0.05	0.27+	0.75***	0.24	0.62***
	CH_4						0.20	0.09	−0.03	0.14
	N_2O							0.16	0.28	0.65***
>8 mm	CO_2								0.08	0.40***
	CH_4									0.13
	N_2O									

Peason's correlation significance is expressed as follows:
***: $p<0.001$, +:$p<0.1$.
Different site, soil depth and soil moisture treatments are included in the analysis.

size 8–20 mm decreased in the 1st year of oil palm development, but increased again in the 9th year (Fig. 1) in the surface. Larger aggregates were broken down to smaller aggregates during land preparation which will increase the frequency of wetting and drying (Denef et al., 2001), while irreversible drying where the humic acid binds the micro-aggregates strongly as the peat soils lose its moisture with consequent larger, stable aggregates happened after the 1st year as detected at the 9th year development site. Thus, the CO_2 emission seems to settle in a plateau of 2000 mg CO_2–C kg^{-1}. In sub-surface, the proportion of aggregate did not differ between forest and 1st year development (Fig. 1). The difference between forest and 9th year might be due to the different underground water table depth, indicating less influence of land use on the aggregate formation at sub-surface.

The CH_4 emission/uptake rates showed clear emission for bigger aggregates, while small aggregates showed consistent CH_4 uptake (Figs. 2b and 3b), with the exception of the high CH_4 uptake for aggregate size 8–20 mm at 30% soil moisture of forest surface soil. Anaerobic condition that promote CH_4 formation (Moore and Dalva 1997) was created in bigger aggregates (Sey et al., 2008), while aerobic condition favoring CH_4 oxidation (Flessa et al., 1998) in smaller aggregates. Application of N fertilizer inhibits the CH_4 oxidation (Gulledge et al., 2004). However, our results showed that the soil total N did not differ among land uses, and inorganic N content was higher in forest soils than in oil palms, which contradicted the above explanation.

The exception found for aggregate size 8–20 mm at 30% soil moisture of forest surface soil might be due to the higher porosity of forest soil, creating a more aerobic condition at big aggregate sizes, leading to different condition than 8–20 mm aggregates from oil palm soils. This result showed also that the development of oil palms lead to decrease in CH_4 uptake compared to forest (Fig. 3b), which must be influenced not by the short term effect of applied N fertilizer directly but by the long term effect of altered soil management methods. The AFPS in the field was highest with 35.5% for 1st year oil palm plantation. The aggregates bigger than 2 mm showed emission of CH_4, indicating a more wet and anaerobic condition than aggregate size 0–2 mm. Higher proportion of small aggregates in the surface layer for the 1st year oil palm (Fig. 1) confirms the relation of aggregate size and moisture. Thus, in field condition, aggregate size will influence the AFPS of the bulk soil, and soils with bigger aggregates will show higher CH_4 emission fluxes due to more anaerobic niches in the bulk soil (Kremen et al., 2005).

The N_2O emission rates showed similar trend as CO_2 emission rates resulting in high emissions in aggregate size 0–2 mm from surface at 70% soil moisture for oil palm soils, and aggregate sizes 2–8 mm and 8–20 mm from sub-surface at 70% soil moisture for all land uses (Fig. 2c). For aggregate size 0–2 mm, stimulated decomposition of organic matter at 70% soil moisture condition combined with the addition of N fertilizer led to enhanced N_2O emission for oil palm soils. As already discussed in the above sentence, bigger aggregate creates anaerobic micro spots that have led to denitrification (Kremen et al., 2005). The N_2O emission rates from all aggregate sizes showed significant positive correlation with the CO_2 emission rates (Table 2) which indicated that soil organic matter decomposition was closely related to the N_2O production through the provision of C as an energy source to denitrifiers. Even though the possibility of the N_2O emission through nitrification cannot be excluded, the main process to produce N_2O must be denitrification because all high peaks were found at 70% soil moisture. The disturbance due to oil palm development was significantly shown by the high N_2O emission rates, which was 2 to 4 times more than the forest site, even though their lower inorganic N contents were lower (Fig. 3c). Soil decomposition due to oil palm development was probably the main causes for the large source of N_2O emission.

5. Conclusion

This study investigated the influence of oil palm development on tropical peat soil. The comparison of different aggregate sizes showed that the investigation of soil aggregate size 0–2 mm alone would be misleading, since the influence of oil palm development was quite different for aggregate size 0–2 mm and those above 2 mm. The development of oil palm on deep tropical peat soils did not change the CO_2 emissions significantly but resulted in higher N_2O emissions compared with the original forest. The effects of oil palm development on CH_4 emissions were inconsistent with the smaller aggregate size, 0–2 mm, showing CH_4 uptake and the larger aggregate sizes CH_4 emissions. The investigation of greenhouse gas emissions in tropical peat soil that is highly undecomposed must take into account the aggregate characteristics of the soil, which are inhomogeneous and mixed with fresh organic matter.

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