

CO₂ Emissions from Tropical Peat Soil Affected by Fertilization

Husnain¹, Ibrahim Adamy Sipahutar¹, Fahmuddin Agus¹, Hery Widyanto² and Nurhayati²

¹Indonesian Soil Research Institute (ISRI), Jl. Tentara Pelajar No 12 Bogor

²Riau Assessment Institute for Agricultural Technology (BPTP Riau), Jl. Kaharudin Nasution No. 34,
e-mail: husnain.isri@gmail.com

Received 27 October 2016/ accepted 02 December 2016

ABSTRACT

The conversion of peatland to agricultural land uses has led to an increase of CO₂ emission due to several factors, including fertilization. However, evidence on the effect of fertilization on CO₂ emission from peat soils is rare and often inconsistent. We measured the effects of different types of fertilizer, including N, P and K sources, and clay as an ameliorant on CO₂ emission from a bare peat soil in Lubuk Ogong, Riau Province. The fertilizers were added in the following combinations: 0 (unfertilized plot), N source (urea), slow-release N (slow-release urea), N and P sources (Urea+SP-36), N, P and K sources (urea+SP-36+KCl) and combined NPK-Clay. The results showed that fertilization resulted in a decrease of CO₂ emissions compared to that prior to fertilization except when slow-release urea was applied. The decrease of CO₂ emissions was probably due to pH-related effects, because the pH in the N treatment was lower than that in both control and unfertilized plots. A decrease in the level of CO₂ emissions among the treatments followed the order of NPK-Clay>NP>NPK>urea>slow-release urea. Covariance analysis showed that the difference in CO₂ emissions prior to treatment was not significant. The application of individual and combined treatments of N, P, K and NPK mixed with 5 Mg ha⁻¹ clay led to a significant reduce of CO₂ emissions from bare peat soil. In addition to fertilization, the depth of water table significantly affected the CO₂ emissions (P<0.05). We conclude that the application of nutrient combinations, including N, P, K and clay, could reduce CO₂ emissions because the fertilizer and clay applications probably could maintain a balanced nutritional condition in the soil with respect to microbial activity.

Keywords: Amelioration, CO₂ emission, fertilization, tropical peat soils

ABSTRAK

Konversi lahan gambut menjadi lahan pertanian telah dilaporkan meningkatkan emisi CO₂ yang disebabkan oleh beberapa faktor termasuk pemupukan. Namun demikian, hasil penelitian pengaruh pemupukan terhadap emisi CO₂ pada lahan gambut masih terbatas dan sering tidak konsisten. Dalam kegiatan penelitian ini telah dilakukan penelitian terhadap pengaruh aplikasi pupuk termasuk beberapa sumber hara N, P dan K serta pemberian liat sebagai amelioran terhadap emisi CO₂ pada lahan gambut terlantar di Lubuk Ogong, Provinsi Riau. Unsur hara diberikan dengan kombinasi perlakuan sebagai berikut: 0 (plot tidak dipupuk), sumber N (urea), pupuk N *slow release* (urea *slow release*), sumber N dan P (Urea+SP-36), sumber N, P dan K (urea+Sp-36+Kcl) dan kombinasi NPK-Liat. Hasil penelitian menunjukkan bahwa aplikasi pupuk di lahan gambut terlantar di lokasi penelitian menunjukkan kecenderungan penurunan emisi CO₂ kecuali pada saat aplikasi urea *slow release* diberikan. Indikasi penurunan emisi CO₂ tersebut kemungkinan disebabkan oleh perubahan pH tanah akibat perlakuan N dimana pH tanah terendah ditemukan pada plot kontrol dan plot yang tidak dipupuk. Nilai penurunan emisi CO₂ antar perlakuan berurutan dari perlakuan NPK-Liat>NP>NPK>urea>urea *slow-release*. Namun demikian, analisis kovarian mengindikasikan bahwa perbedaan nilai emisi antar perlakuan tersebut tidak nyata. Pemberian pupuk secara tunggal dan kombinasi N, P dan NPK-liat 5 Mg ha⁻¹ menghasilkan penurunan emisi CO₂ pada lahan gambut terlantar di Lubuk Ogong, Provinsi Riau. Selain faktor pemupukan, kedalaman muka air tanah adalah salah satu faktor yang paling nyata mempengaruhi penurunan emisi CO₂ (P<0.05). Sebagai kesimpulan adalah bahwa aplikasi kombinasi unsur hara N, P, K dan liat mampu menurunkan emisi CO₂ terutama disebabkan peningkatan keseimbangan hara dalam tanah yang berpengaruh terhadap aktivitas mikroba tanah.

Kata kunci: Amelioran, emisi CO₂, pemupukan, tanah gambut tropis

INTRODUCTION

Tropical peatlands are considered to contribute greenhouse gas (GHG) emissions that accelerate global warming. High temperature and humidity levels in the tropics provide suitable conditions for various organic matter decomposition processes that cause a high loss of GHGs to the atmosphere. There are about 19.4 million hectares of peatland in Indonesia, and approximately 4 million hectares are located in Riau Province, which equals to 45% of the total area of Riau Province (Agus and Subiksa 2008). In 2000, land use and land use change and forestry (LULUCF) emissions in Indonesia were estimated to be 2.6 Mt CO₂, corresponding to 34% of the global LULUCF emissions, and the majority of these emissions were caused by deforestation and forest degradation (PEACE 2007). Typically, the levels of CO₂ emissions from forested peatlands are lower than the levels of sequestration, and natural peatlands produce between 0.5 to 1.0 t C ha⁻¹ yr⁻¹ (Parish *et al.* 2007), whereas CO₂ sequestration from the atmosphere ranges from 0.008 to 0.80 t C ha⁻¹ yr⁻¹ (Harden *et al.* 1992).

The GHGs that are most commonly associated with agriculture are carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). Among these GHGs, CO₂ is cycled and released into the atmosphere in the largest volume. Methane (CH₄) is mainly emitted due to rice cultivation and ruminant livestock, whereas N₂O is released via the activity of soil microorganism (Snyder *et al.* 2007). Agriculture contributes less than 10% of the total emission of GHGs in the U.S. (US EPA 2007) and contributes less than 8% in Canada (Environment Canada 2007). Although total GHG emissions from agriculture are typically less than 10%, agriculture is considered to be the major source of CO₂, CH₄, and N₂O.

The conversion of peatlands to agricultural lands has several consequences, such as subsidence of peat and the need to apply fertilizers and ameliorants. An appropriate management of drainage and fertilization on peat soils is expected to increase crop yield and maintain the soil condition. However, in case of peat soil, emission of GHGs should be considered. Concerns have been raised regarding an increase of CO₂ emissions on peat soils due to fertilization. Unfortunately, the effects of fertilizer application on peat soils on GHG emissions are not fully understood.

Nitrogen fertilizer, such as urea (CO(NH₂)₂), emits CO₂ when it is converted into ammonium (NH₄⁺), hydroxyl ion (OH⁻), and bicarbonate (HCO₃⁻) in the presence of water and urease enzymes (Snyder *et*

al. 2007). A high efficiency of nitrogen use could increase C sequestration and reduce CO₂ emissions (Paustian *et al.* 1992). Nitrogen plays an important role in soil C storage and stabilizing C in the soil (Paustian *et al.* 1997; Lal 2004). The application of high levels of fertilizer significantly enhances carbon emissions mainly through the stimulation of root respiration process. Some reports on the effect of fertilization on soil CO₂ and N₂O emissions showed a complex process involved (Sakata *et al.* 2015; Uchida *et al.* 2013; Nagano *et al.* 2012).

Aerts and Caluwe (1999) suggested that CO₂ and CH₄ emissions are high in peat soils due to the low fertility of these soils. Therefore, mismanagement of the fertilizer rate, source, application placement and time can increase the overall N loss and N₂O and CO₂ emissions. Several studies have reported that N₂O and CO₂ emissions can be reduced using sufficient amounts of fertilizer and applying a high-efficiency fertilizer (Khan *et al.* 2007; Bufogle *et al.* 1998). However, several studies have shown contrasting results. The application of N fertilizer suppressed CO₂ emissions in several ecosystems, such as forests and grasslands (Kowalenko *et al.* 1978; Micks *et al.* 2004; Burton *et al.* 2004). These results could be explained as indirect effect of fertilization on CO₂ emissions. Nitrogen fertilization affects the soil C pool, resulting in an increase of biomass and microbial decomposition of crop residues (Green *et al.* 1995; Lal 2004). However, the reason for the suppression of soil CO₂ emissions due to N fertilization remains unclear.

In the present study, we investigated the effects of fertilizer application on the micro variability of CO₂ emissions using representative plots in a tropical bare peat soil. The study of the micro variability of CO₂ emissions may provide useful information for peat soil management.

MATERIALS AND METHODS

Study Area

The study was conducted in an agricultural peatland in Lubuk Ogong Village, Pelalawan District, Riau Province, which is the second largest peatland in Riau Province (Wahyunto and Suryadiputra 2008). The study sites are located between latitude 0°20'44.5"N and longitude 101°41'10.9"E. The annual rainfall of this area is 2,500-3,000 mm and the daily temperature is between 22-31°C. The observation plots were located in bare land peat soils.

The observation area comprised of 24 plots in which the size of each plot was 2 m x 2 m. There

Table 1. Fertilizer rates applied in measuring plots.

Treatment	Application rate
Control	0
Urea	2.5 kg ha ⁻¹
Urea Slow release	3 kg ha ⁻¹
NP	2.5 kg Urea+ 2.75 kg SP-36
NPK	2.5 kg Urea+ 2.75 kg SP-36+ 2.25 kg KCl
NPKClay	2.5 kg Urea+ 2.75 kg SP-36+ 2.25 kg KCl+ Clay 5,000 kg ha ⁻¹

The source of N is Urea (urea contains 46% N), the source of P is SP-36 (SP-36 contains 36% P₂O₅), the source of K is KCl (KCl contains 50% K₂O)

were 6 fertilizer treatments and 4 replicates for each treatment, as shown in Table 1. The rate of fertilizer application was determined based on the fertilization recommendation for oil palm plantations. Fertilizers were spread evenly on the soil surface and then thoroughly mixed into the soil.

Measurement of Soil Properties and CO₂ Emissions

The level of maturity and determined thickness of peat and mineral substrate were determined in the field according to the method proposed by Agus *et al.* (2011). Soil samples were taken from 24 plots both in the top soil (0-20 cm) and sub soil (20-50 cm) before fertilization.

The soil samples were air-dried and ground to pass through a 2-mm sieve. Soil pH was measured using a glass electrode with soil:water ratio of 1:5 (McLean 1982). Total C content of the soil samples was determined using Walkley and Black method (Nelson and Sommers 1982). Total nitrogen (N) content was determined using Kjeldahl method (Bremner and Mulvaney 1982)). Available soil phosphorus (P) was extracted using Bray 2 method (Bray and Kurtz 1945). Cation exchange capacity (CEC) and exchangeable calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na) were extracted using 1 M ammonium acetate (NH₄OAc) at pH 7.0. Total P and K were extracted using 25% HCl. Calcium (Ca) and Mg concentrations were determined using an atomic absorption spectro photometer (Hitachi Z-5000), and K and Na concentrations were determined using a flame photometer. The microelements were extracted using DTPA, and their concentrations were measured by inductively coupled plasma (ICP) (Spectro Genesis Ametek). Samples for soil bulk density (BD) measurement were taken using a peat auger by drilling the 0–20 cm soil layer. Each sample in the tube was transferred quantitatively to a plastic bag and the BD was determined using the gravimetric method (Agus *et al.* 2011).

Intensive measurements of CO₂ emission were conducted at all 24 plots for a period of CO₂ emission approximately 6 months. The measurement dates were 1, 7, 14, 20 and 27 June 2011, 22-23 July 2011, 16-17 September 2011, 9-10 November and 21-22 December 2011.

CO₂ emissions were monitored using an Li-COR 820 portable infrared gas analyzer (IRGA). The depth of water table, soil temperature and soil water content were measured at each measurement time point. Other parameters, including the soil pH, peat maturity, organic C content, bulk density and other soil chemical properties of peat soil were also observed.

The CO₂ gas emission in the surface of the peatland was trapped using a PVC closed chamber with a diameter of 25 cm and height of 23 cm. The gas fluxes were monitored every second for approximately 2 minutes. The relationship between the time and CO₂ concentration was exponential. The CO₂ flux is estimated using the following equation:

$$fc = \frac{Ph}{RT} \frac{dC}{dt}$$

where *fc* = CO₂ flux (μmol⁻¹ m⁻² per sec), *P*=atmospheric pressure based on the average reading of the IRGA (kPa), *h*= height of the chamber (cm), *R* = gas constant (8,314 Pa m³ per °K per mole), *T*= temperature and *dC/dt* = change of CO₂

Table 2. Peat maturity observed in the study site, Lubuk Ogong Village, Riau Province.

Peat depth (cm)	Peat maturity
0-20	Sapric
20-50	Sapric
50-100	Hemic
100-500	Fibric
500-550	Sandy peaty clay
550->800	Clayey

Tabel 3. Chemical properties of peat soil in Lubuk Ogong, Pelalawan, Riau Province.

Parameters	Units	Surface (0-20 cm)	Subsurface (20-50 cm)
pH H ₂ O		3.40±0.02	3.25±0.13
pH KCl		2.67±0.06	2.55±0.06
C (Walkley&Black)	%	49.47±3.87	50.39±3.70
N (Kjeldahl)	%	1.19±0.21	1.03±0.08
C/N	%	43±8.58	49±6.18
P ₂ O ₅ (HCl25%)	mg 100g ⁻¹	30.21±4.46	18±3.27
KCl (HCl 25%)	mg 100g ⁻¹	35.33±6.86	32±11.37
P ₂ O ₅ (Bray)	ppm	103.70±21.68	76.08±23.20
Exch Ca	cmol c(+) kg ⁻¹	6.27±3.40	3.12±0.97
Exch Mg	cmol c(+) kg ⁻¹	1.88±0.56	1.67±0.77
Exch K	cmol c(+) kg ⁻¹	0.51±0.12	0.52±0.11
Exch Na	cmol c(+) kg ⁻¹	0.57±0.12	0.74±0.63
CEC	cmol c(+) kg ⁻¹	94.35±6.39	89.10±12.80
<i>DTPA extract</i>			
Fe	ppm	339.08±124.38	499.38±261.71
Mn	ppm	10.24±7.57	11.63±5.40
Cu	ppm	0.53±0.13	0.60±0.14
Zn	ppm	4.07±1.93	3.98±2.24
Ash	%	5.80±1.64	3.01±1.54
Bulk density	g cm ⁻³	0.12-0.14	0.05-0.09

concentration per area over time (mol ppm per m² per sec).

RESULTS AND DISCUSSIONS

Peat Properties

The peat maturity in the surface soil (0-50 cm depth) is sapric, whereas hemic (50-100 cm) and fibric (100-150 cm) peats are present in the deeper layers (Table 2). The properties of the peat soil in the study site are presented in Table 3. The soil pH in both the surface and subsurface is highly acidic with pH values less than 3.5. The soil carbon contents in the surface and subsurface of the peat soil range from 49 to 50 %. The CEC on a weight basis of peat soil was greater than that of typical mineral soils; however, if the values are considered on a volume basis, the CEC of peat soil would be significantly less than that of mineral soil. Organic soil commonly has 55% of the exchange capacity saturated with hydrogen. The contents of potassium, Mg and Na are low due to a high loss of these elements through leaching. The exchange capacity of organic soil materials depends on the number of negatively charged exchange sites. The sites adsorb cation Ca, Mg, K, and Na that replace the adsorbed hydrogen ions, as reported by Andriess (1988). The total and available phosphorus contents are high,

probably due to low levels of P sorption by Al and Fe. In general, the availability of micronutrient extracted with DTPA is low because trace elements, including Fe, Mn, Cu and Zn could be bound by organic acids.

The chemical properties of the soil before and after fertilization did not show a significant difference (data not shown), except for the soil C content. At the end of the experiment, the soil C content has decreased by approximately 3-10% in the fertilized plots. The loss of soil C in the top (0-20 cm) peat soil is higher compared to that in the subsoil (20-50 cm). The loss of soil C is likely related to the microbial activity. However, for the long term of observation (6 months) employed in this study, the effect of fertilizer to the decrease of soil C content could be ignored, and the microbial activity is likely controlling the soil carbon content through decomposition process.

The Effects of Fertilization on CO₂ Emissions

The CO₂ emissions from the peat soil before treatment ranged from 54 to 72 Mg ha⁻¹ yr⁻¹ (Figure 1). The initial level of CO₂ emission in the peat soil observed in this study is higher compared to that in the peat soils from other sites in Indonesia (Husnain *et al.* 2014). The relatively high temperature of the soil and air as well as the relatively young age of the peatland may be responsible for these high levels

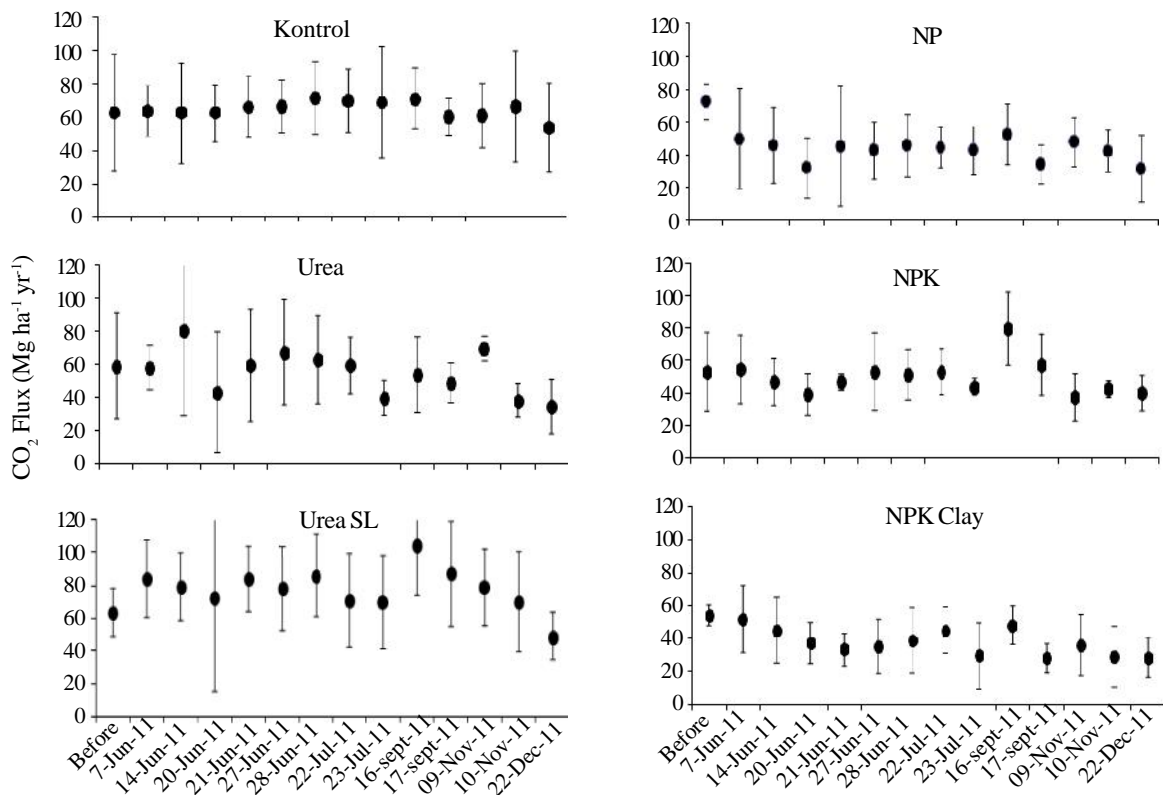


Figure 1. Trend of CO₂ emission under fertilized measuring plots of peat soil during six months observation (bullets indicate mean and bars indicate standard deviation).

of CO₂ emissions. As a comparison, CO₂ emissions from peat soils in Jambi Province range from 34 to 45 Mg ha⁻¹ yr⁻¹ (Dariah *et al.* 2013; Marwanto *et al.* 2013) and 53 to 65 Mg ha⁻¹ yr⁻¹ in Central Kalimantan (Agus *et al.* 2013). The cultivation systems and land uses have changed significantly CO₂ emissions as reported by Wilson and Al-Kaisi (2008).

The levels of CO₂ emissions from the bare peat soil before and after fertilization are summarized in Table 4. After fertilization, the average level of CO₂ emission varied from 37.38

to 78.23 Mg ha⁻¹ yr⁻¹. Covariance analysis showed that there was no significant difference in CO₂ emissions before fertilization among the treatments. However, after fertilization, the highest CO₂ emission was observed in the plots with nitrogen application. The application of N, P, K and the combination of these nutrients resulted in a decrease of CO₂ emissions. Among the treatments, the highest CO₂ flux was observed in plots with urea SL, although this flux was not significantly different from that in the Control and Urea plots. The lowest CO₂ flux

Table 4. Average flux of CO₂ emission before and after fertilizer application on bare peat soil in Lubuk Ogong, Riau Province.

Treatment	Mean CO ₂ emission before fertilization (Mg ha ⁻¹ yr ⁻¹)	Mean CO ₂ emission after fertilization (Mg ha ⁻¹ yr ⁻¹)
No fertilizer (control)	61±7 ab	65±5ab
N	59±32 ab	55±13abc
N slow release	63±14ab	78±12a
N+P	72±10a	42 ±6bc
N+P+K	53±24 abc	49±11bc
N+P+K+Clay	54±6 abc	37±8 c

The source of N is Urea (urea contains 46% N), the source of P is SP-36 (SP-36 contains 36% P₂O₅), The source of K is KCl (KCl contains 50% K₂O). The numbers with the same letters in columns and rows are not significantly different.

Table 5. Pearson correlation of several parameters versus CO₂ flux observed after fertilization.

Parameter	CO ₂ Flux	P value
Soil temperature	0.07	0.8425
Air temperature	-0.05	0.0923
Distance from drainage	-0.15	0.7318
Soil Moisture	0.02	0.0732
Water Table Depth	0.34	0.0060

was observed in the NPK-Clay plot (Table 4). In summary, after fertilization, the order of the level of CO₂ emission was as follow: Urea SL> Urea> NPK> NP>NPK-Clay. In general, CO₂ emissions in the fertilized plots varied with the fertilizer type and measurement time. In contrast, in the control plot, the CO₂ emissions before and after fertilization were not significantly different. CO₂ emissions were various at each time point of measurement and affected by changes in the soil temperature and depth of water table (Table 5). The deeper of water-table exposes a thicker peat layer to aerobic conditions (Agus *et al.* 2011), which can contribute to the increase of CO₂ emissions.

The levels of CO₂ emissions were relatively high and varied widely in the Urea and slow-release Urea plots. Urea is commonly used as nitrogen fertilizer source. Nitrogen plays a role in stabilizing C in soil by increasing the soil carbon level through biomass production. In the long term, nitrogen fertilization can lead to an increase of net C storage via humification processes (Paustian *et al.* 1992). However, the application of N fertilizer in the form of urea (CO(NH₂)₂) leads to a loss of CO₂ because urea is converted into NH₄⁺, OH⁻ and HCO₃⁻. All C in urea is considered to be emitted as CO₂ unless the proper management of urea is performed (Snyder *et al.* 2007). Nitrogen fertilization also leads to emission of N₂O as a result of the microbial processes of nitrification and denitrification. However, in this study, we did not observe N₂O emission because the emission of N₂O was expected to be small compared to the CO₂ emissions. According to IPCC (2006), approximately 1% of N fertilizer will be emitted as N₂O-N. In addition, N₂O emissions vary widely on a site-specific basis (Snyder *et al.* 2007).

A slow-release N fertilizer used in this study was a coated urea. In principle, slow-release nitrogen fertilizer would minimize GHG emissions due to the presence of a nitrification inhibitor that would minimize the conversion of NH₄⁺ into NO₂⁻. As a result, N would be retained as NH₄⁺ for a longer period and plants would have enough time to

assimilate NH₄⁺ and thereby prevent N₂O emission. Uchida *et al.* (2013) reported that coated urea reduced CO₂ emissions. In contrast, our study observed that CO₂ emissions were high and fluctuated when slow-release urea was applied. Although nitrogen was released in bare peat soil, the nitrogen was not utilized by plants. An additional factor that caused high levels of CO₂ emissions was the fertilizer placement. Fertilizer was applied on the soil surface. The loss of N fertilizer is greater when N fertilizer is applied on the soil surface compared to band placement (Snyder *et al.* 2007; Hultgreen and Leduc 2003). These two factors may explain the high levels of CO₂ emissions from the plots applied with nitrogen fertilizer.

In contrast CO₂ emissions in the plots applied with NP, NPK and NPK+Clay were lower than in the plots applied with nitrogen fertilizer. The application of combined N, P and K fertilizer should improve the nutrient balance and cycling in the soil compared to the single application of nitrogen fertilizer. For example, when mixed N and P fertilizer was applied, the soil pH increased, whereas acidic conditions were observed when nitrogen fertilizer in the form of urea was added. In general, a balanced application of N, P, K and trace elements fertilizers is believed to be the best management practice for agricultural soils, including peat soils. Certain studies have reported a positive effect of applying P, K and trace elements together with N fertilizer. Shlegel *et al.* (1996) found that application of P fertilizer increased yields and reduced soil NO₃-N levels, thereby leading to reduced GHG emissions. Application of P fertilizer inhibits the decomposition process of soil organic matter (Amador and Jones 1993) and soil respiration (Franklin *et al.* 2003) and does not affect CO₂ emissions (Aerts and Toet 1997). Johnson *et al.* (1996) suggested that application of K fertilizer improved crop N uptake and NO₃-N retention in the upper soil profile. The condition above could have occurred as application of fertilizer can inhibit CH₄ oxidation by competing for methane monooxygenase, the enzyme used by methanotrophs to oxidize CH₄. In addition, nutrient

can also directly influence microbial communities at timescales reflecting the turnover of microbial populations (Keller *et al.* 2006).

The lowest level of CO₂ emissions was observed with the application of NPK fertilizer combined with 5 Mg ha⁻¹ clay. In this case, clay plays a significant role in reducing CO₂ emissions. This phenomenon may be due to the addition of clay is related to the complexation and binding of organic acids with metal ions contained in the clay. The incorporation of clay minerals within the peat soil could reduce the concentration of organic acids through chelation processes with metal ions. As a result, the peat soil would be more resistant to decomposition processes, therefore reducing the production of CO₂ and CH₄ (Sabiham 2010).

The fluctuations of CO₂ emissions from the fertilized plots are probably caused by chemical and biological reactions in the peat soil. These changes varied within the type of fertilizer and time of sampling. Harrison and Webb (2001) suggested that the emission factors of different fertilizer types depend on the conditions during the period after fertilization. However, Stehfest and Bouwman (2006) found that differences among fertilizer types largely vanish after fertilization due to the equal effects of the application rate, crop type, climate, soil organic carbon, soil pH and length of the experiment. Similarly, Bridgman *et al.* (1996; 1998) reported that different peatland types may respond differently to similar fertilization and liming applications.

The variation in the CO₂ emissions is also affected by the depth of water table (P<0.05). The matrix correlation of several possible factors affecting CO₂ emissions are presented in Table 4. An increase of the depth of water table observed in the early rainy season (Nov-Dec 2011) corresponds to the decrease of CO₂ emissions.

CONCLUSIONS

The results of current study showed that application of combined N, P, K fertilizer and clay could reduce CO₂ emission. After fertilization, the relative levels of CO₂ emissions were as follows: Urea SL> Urea> NPK> NP>NPK Clay. Combined fertilization, including N, P, K and clay, could maintain a balance nutritional condition in the soils, including pH, the loss of ammonium to the air, decomposition processes, soil respiration, and other factors controlling peat soil reactions that are responsible for reducing CO₂ emissions. The average level of CO₂ emission varied from 37.38 to 78.23 Mg ha⁻¹ yr⁻¹. However, large variations in the levels of CO₂ emissions were recorded during the

experiment. Therefore, an intensive and long-term measurement of CO₂ emissions should be continued.

ACKNOWLEDGEMENT

We thank people involved in this research for their assistance during the field observations. This work was supported by the REDD Alert Project under FP7 EU.

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