

# CO<sub>2</sub> Emissions from Tropical Peat Soil Affected by Fertilization

Husnain<sup>1</sup>, Ibrahim Adamy Sipahutar<sup>1</sup>, Fahmuddin Agus<sup>1</sup>, Hery Widyanto<sup>2</sup> and Nurhayati<sup>2</sup>

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

<sup>2</sup>Riau 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 CO<sub>2</sub> emission due to several factors, including fertilization. However, evidence on the effect of fertilization on CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub> emissions compared to that prior to fertilization except when slow-release urea was applied. The decrease of CO<sub>2</sub> 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 CO<sub>2</sub> emissions among the treatments followed the order of NPK-Clay>NP>NPK>urea>slow-release urea. Covariance analysis showed that the difference in CO<sub>2</sub> 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<sup>-1</sup> clay led to a significant reduce of CO<sub>2</sub> emissions from bare peat soil. In addition to fertilization, the depth of water table significantly affected the CO<sub>2</sub> emissions (P<0.05). We conclude that the application of nutrient combinations, including N, P, K and clay, could reduce CO<sub>2</sub> emissions because the fertilizer and clay applications probably could maintain a balanced nutritional condition in the soil with respect to microbial activity.

**Keywords:** Amelioration, CO<sub>2</sub> emission, fertilization, tropical peat soils

## ABSTRAK

Konversi lahan gambut menjadi lahan pertanian telah dilaporkan meningkatkan emisi CO<sub>2</sub> yang disebabkan oleh beberapa faktor termasuk pemupukan. Namun demikian, hasil penelitian pengaruh pemupukan terhadap emisi CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub> kecuali pada saat aplikasi urea *slow release* diberikan. Indikasi penurunan emisi CO<sub>2</sub> 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 CO<sub>2</sub> 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<sup>-1</sup> menghasilkan penurunan emisi CO<sub>2</sub> 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 CO<sub>2</sub> (P<0.05). Sebagai kesimpulan adalah bahwa aplikasi kombinasi unsur hara N, P, K dan liat mampu menurunkan emisi CO<sub>2</sub> terutama disebabkan peningkatan keseimbangan hara dalam tanah yang berpengaruh terhadap aktivitas mikroba tanah.

**Kata kunci:** Amelioran, emisi CO<sub>2</sub>, 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 CO<sub>2</sub>, 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 CO<sub>2</sub> emissions from forested peatlands are lower than the levels of sequestration, and natural peatlands produce between 0.5 to 1.0 t C ha<sup>-1</sup> yr<sup>-1</sup> (Parish *et al.* 2007), whereas CO<sub>2</sub> sequestration from the atmosphere ranges from 0.008 to 0.80 t C ha<sup>-1</sup> yr<sup>-1</sup> (Harden *et al.* 1992).

The GHGs that are most commonly associated with agriculture are carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O). Among these GHGs, CO<sub>2</sub> is cycled and released into the atmosphere in the largest volume. Methane (CH<sub>4</sub>) is mainly emitted due to rice cultivation and ruminant livestock, whereas N<sub>2</sub>O 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 CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O.

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 CO<sub>2</sub> 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(NH<sub>2</sub>)<sub>2</sub>), emits CO<sub>2</sub> when it is converted into ammonium (NH<sub>4</sub><sup>+</sup>), hydroxyl ion (OH<sup>-</sup>), and bicarbonate (HCO<sub>3</sub><sup>-</sup>) in the presence of water and urease enzymes (Snyder *et*

*al.* 2007). A high efficiency of nitrogen use could increase C sequestration and reduce CO<sub>2</sub> 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 CO<sub>2</sub> and N<sub>2</sub>O emissions showed a complex process involved (Sakata *et al.* 2015; Uchida *et al.* 2013; Nagano *et al.* 2012).

Aerts and Caluwe (1999) suggested that CO<sub>2</sub> and CH<sub>4</sub> 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 N<sub>2</sub>O and CO<sub>2</sub> emissions. Several studies have reported that N<sub>2</sub>O and CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub> emissions due to N fertilization remains unclear.

In the present study, we investigated the effects of fertilizer application on the micro variability of CO<sub>2</sub> emissions using representative plots in a tropical bare peat soil. The study of the micro variability of CO<sub>2</sub> 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 <sup>-1</sup>
Urea Slow release	3 kg ha <sup>-1</sup>
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 <sup>-1</sup>

The source of N is Urea (urea contains 46% N), the source of P is SP-36 (SP-36 contains 36% P<sub>2</sub>O<sub>5</sub>), the source of K is KCl (KCl contains 50% K<sub>2</sub>O)

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 CO<sub>2</sub> 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 (NH<sub>4</sub>OAc) 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 CO<sub>2</sub> emission were conducted at all 24 plots for a period of CO<sub>2</sub> 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.

CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub> concentration was exponential. The CO<sub>2</sub> flux is estimated using the following equation:

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

where *fc* = CO<sub>2</sub> flux (μmol<sup>-1</sup> m<sup>-2</sup> 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 m<sup>3</sup> per °K per mole), *T*= temperature and *dC/dt* = change of CO<sub>2</sub>

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 <sub>2</sub> 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 <sub>2</sub> O <sub>5</sub> (HCl25%)	mg 100g <sup>-1</sup>	30.21±4.46	18±3.27
KCl (HCl 25%)	mg 100g <sup>-1</sup>	35.33±6.86	32±11.37
P <sub>2</sub> O <sub>5</sub> (Bray)	ppm	103.70±21.68	76.08±23.20
Exch Ca	cmol c(+) kg <sup>-1</sup>	6.27±3.40	3.12±0.97
Exch Mg	cmol c(+) kg <sup>-1</sup>	1.88±0.56	1.67±0.77
Exch K	cmol c(+) kg <sup>-1</sup>	0.51±0.12	0.52±0.11
Exch Na	cmol c(+) kg <sup>-1</sup>	0.57±0.12	0.74±0.63
CEC	cmol c(+) kg <sup>-1</sup>	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 <sup>-3</sup>	0.12-0.14	0.05-0.09

concentration per area over time (mol ppm per m<sup>2</sup> 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 CO<sub>2</sub> Emissions

The CO<sub>2</sub> emissions from the peat soil before treatment ranged from 54 to 72 Mg ha<sup>-1</sup> yr<sup>-1</sup> (Figure 1). The initial level of CO<sub>2</sub> 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

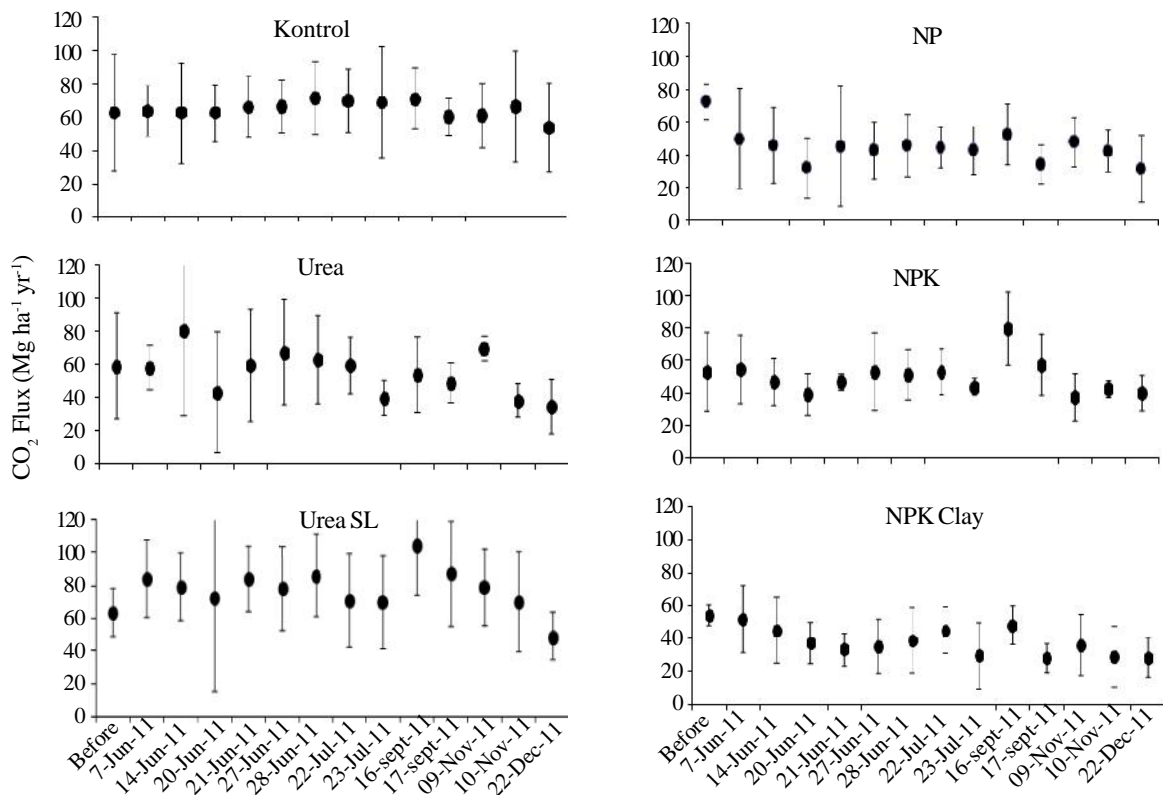


Figure 1. Trend of CO<sub>2</sub> emission under fertilized measuring plots of peat soil during six months observation (bullets indicate mean and bars indicate standard deviation).

of CO<sub>2</sub> emissions. As a comparison, CO<sub>2</sub> emissions from peat soils in Jambi Province range from 34 to 45 Mg ha<sup>-1</sup> yr<sup>-1</sup> (Dariah *et al.* 2013; Marwanto *et al.* 2013) and 53 to 65 Mg ha<sup>-1</sup> yr<sup>-1</sup> in Central Kalimantan (Agus *et al.* 2013). The cultivation systems and land uses have changed significantly CO<sub>2</sub> emissions as reported by Wilson and Al-Kaisi (2008).

The levels of CO<sub>2</sub> emissions from the bare peat soil before and after fertilization are summarized in Table 4. After fertilization, the average level of CO<sub>2</sub> emission varied from 37.38

to 78.23 Mg ha<sup>-1</sup> yr<sup>-1</sup>. Covariance analysis showed that there was no significant difference in CO<sub>2</sub> emissions before fertilization among the treatments. However, after fertilization, the highest CO<sub>2</sub> 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 CO<sub>2</sub> emissions. Among the treatments, the highest CO<sub>2</sub> 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 CO<sub>2</sub> flux

Table 4. Average flux of CO<sub>2</sub> emission before and after fertilizer application on bare peat soil in Lubuk Ogong, Riau Province.

Treatment	Mean CO <sub>2</sub> emission before fertilization (Mg ha <sup>-1</sup> yr <sup>-1</sup> )	Mean CO <sub>2</sub> emission after fertilization (Mg ha <sup>-1</sup> yr <sup>-1</sup> )
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% P<sub>2</sub>O<sub>5</sub>), The source of K is KCl (KCl contains 50% K<sub>2</sub>O). The numbers with the same letters in columns and rows are not significantly different.

Table 5. Pearson correlation of several parameters versus CO<sub>2</sub> flux observed after fertilization.

Parameter	CO <sub>2</sub> 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 CO<sub>2</sub> emission was as follow: Urea SL> Urea> NPK> NP>NPK-Clay. In general, CO<sub>2</sub> emissions in the fertilized plots varied with the fertilizer type and measurement time. In contrast, in the control plot, the CO<sub>2</sub> emissions before and after fertilization were not significantly different. CO<sub>2</sub> 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 CO<sub>2</sub> emissions.

The levels of CO<sub>2</sub> 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(NH<sub>2</sub>)<sub>2</sub>) leads to a loss of CO<sub>2</sub> because urea is converted into NH<sub>4</sub><sup>+</sup>, OH<sup>-</sup> and HCO<sub>3</sub><sup>-</sup>. All C in urea is considered to be emitted as CO<sub>2</sub> unless the proper management of urea is performed (Snyder *et al.* 2007). Nitrogen fertilization also leads to emission of N<sub>2</sub>O as a result of the microbial processes of nitrification and denitrification. However, in this study, we did not observe N<sub>2</sub>O emission because the emission of N<sub>2</sub>O was expected to be small compared to the CO<sub>2</sub> emissions. According to IPCC (2006), approximately 1% of N fertilizer will be emitted as N<sub>2</sub>O-N. In addition, N<sub>2</sub>O 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 NH<sub>4</sub><sup>+</sup> into NO<sub>2</sub><sup>-</sup>. As a result, N would be retained as NH<sub>4</sub><sup>+</sup> for a longer period and plants would have enough time to

assimilate NH<sub>4</sub><sup>+</sup> and thereby prevent N<sub>2</sub>O emission. Uchida *et al.* (2013) reported that coated urea reduced CO<sub>2</sub> emissions. In contrast, our study observed that CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub> emissions from the plots applied with nitrogen fertilizer.

In contrast CO<sub>2</sub> 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 NO<sub>3</sub>-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 CO<sub>2</sub> emissions (Aerts and Toet 1997). Johnson *et al.* (1996) suggested that application of K fertilizer improved crop N uptake and NO<sub>3</sub>-N retention in the upper soil profile. The condition above could have occurred as application of fertilizer can inhibit CH<sub>4</sub> oxidation by competing for methane monooxygenase, the enzyme used by methanotrophs to oxidize CH<sub>4</sub>. 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 CO<sub>2</sub> emissions was observed with the application of NPK fertilizer combined with 5 Mg ha<sup>-1</sup> clay. In this case, clay plays a significant role in reducing CO<sub>2</sub> 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 CO<sub>2</sub> and CH<sub>4</sub> (Sabiham 2010).

The fluctuations of CO<sub>2</sub> 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 CO<sub>2</sub> emissions is also affected by the depth of water table (P<0.05). The matrix correlation of several possible factors affecting CO<sub>2</sub> 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 CO<sub>2</sub> emissions.

## CONCLUSIONS

The results of current study showed that application of combined N, P, K fertilizer and clay could reduce CO<sub>2</sub> emission. After fertilization, the relative levels of CO<sub>2</sub> 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 CO<sub>2</sub> emissions. The average level of CO<sub>2</sub> emission varied from 37.38 to 78.23 Mg ha<sup>-1</sup> yr<sup>-1</sup>. However, large variations in the levels of CO<sub>2</sub> emissions were recorded during the

experiment. Therefore, an intensive and long-term measurement of CO<sub>2</sub> 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.

## REFERENCES

- Aerts R and H de Caluwe. 1999. Nitrogen deposition effects on carbon dioxide and methane emission from temperate peatland soils. *Oikos* 84: 44-54.
- Aerts R and S Toet. 1997. Nutritional controls on carbon dioxide and methane emission from Carex-dominated peat soil. *Soil Biol Biochem* 29: 1683-1690.
- Agus F and IGM Subiksa. 2008. Lahan gambut: *Potensi untuk pertanian dan aspek lingkungan*. Balai Penelitian Tanah. Badan Litbang Pertanian.
- Agus F, N Harris, IE Henson, TJ Killeen, BH Sahardjo and M van Noordwijk. 2013. *Review of emission factors for assessment of CO<sub>2</sub> emission from land use change to oil palm in Southeast Asia*. Roundtable on sustainable Palm Oil, Kuala Lumpur, Malaysia, October 2013.
- Agus F, K Hairiah and A Mulyani. 2011. Measuring carbon stock in peat soils: practical guidelines. Bogor, Indonesia. *World Agroforestry Centre (ICRAF) Southeast Asia Regional Program and Indonesian Centre for Agricultural Land Resources Research and Development*. Bogor, Indonesia.
- Amador JA and RD Jones. 1993. Nutrient limitations on microbial respiration in peat soils with different total phosphorus content. *Soil Biol Biochem* 25: 793-801.
- Andriess JP. 1988. Nature and Management of Tropical Peat Soils. *FAO Soils Bulletin* 59. FAO-Food and Agriculture Organization of the United Nations. Rome.
- Bray RH and LT Kurtz. 1945. Determination of total, organic and available phosphorus in soils. *Soils Sci* 59: 39-45.
- Bremner JM and CS Mulvaney. 1982. Methods of soil analysis, part 2: Chemical and Microbiological Properties. *Agronomy* 9, Soil Science Society of America, Madison, WI, 595 pp.
- Bridgman SD, J Pastor, JA Janssens, C Chapin and TJ Malterer. 1996. Multiple limiting gradient in peatlands: a call for a new paradigm. *Wetlands* 16: 45-65.
- Bridgman SD, K Updegraff and J Pastor. 1998. Carbon, nitrogen and phosphorus mineralization in northern wetlands. *Ecology* 79: 1545-1561.
- Bufole A Jr, PK Bollich, JL Kovar, CW Lindau and RE Macchiavelli. 1998. Comparison of ammonium sulphate and urea as nitrogen sources in rice production. *J Plant Nutr* 21: 1601-1614.

- Burton AJ, KS Pregitzer, JN Crawford, GP Zogg and DR Zak. 2004. Simulated chronic NO<sub>3</sub><sup>-</sup> addition reduces soil respiration in northern hardwood forests. *Glob Change Biol* 10: 080-1091.
- Dariah A, S Marwanto and F Agus. 2013. Root- and peat-based CO<sub>2</sub> emissions from oil palm plantations. *Mitig Adapt Strateg Glob Change*. doi:10.1007/s11027-013-9515-6.
- Environment Canada. 2007. National Inventory Report. 1990-2005, Greenhouse Gas Sources and Sinks in Canada. <http://www.ec.gc.ca/>. accessed 7 Auguts 2007.
- Franklin O, PHögberg, A Eklbad and GI Agren. 2003. Pine forest floor carbon accumulation in response to N, P and K additions: Bom C-14 modelling and respiration studies. *Ecosystems* 6: 644-658.
- Green CJ, AM Blackmer and R Horton. 1995. Nitrogen effects on conservation of carbon during corn residue decomposition in soil. *Soil Sci Soc Am J* 9: 453-459.
- Harden JW, ET Sundquist, RF Stallard and RK Mark. 1992. Dynamics of soil carbon during the deglaciation of the Laurentide ice sheet. *Science* 258: 1921-1924, doi: 10.1126/science.258.5090.1921.
- Harrison R and J Webb. 2001. A review of the effect of N fertilizer type on gaseous emission. *Adv Agron* 73: 65-108.
- Hultgreen G and P Leduc. 2003. *The effect of nitrogen fertilizer placement, formulation, timing, and rate on greenhouse gas emissions and agronomic performance*. Final Report, Project No. 5300 G, ADF#19990028, Saskatchewan Department of Agriculture and Food, Regina, SK. <http://www.agr.gov.sk.ca/>.
- Husnain, IGP Wigena, A Dariah, S. Marwanto, P. Setyanto and F Agus. 2014. CO<sub>2</sub> emissions from tropical drained peat in Sumatra, Indonesia. *Mitig Adapt Strateg Glob Change* doi: 10.1007/s11027-014-9550-y
- IPCC. 2006. *Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories*. Volume 4: Agriculture, Forestry and Other Land Use. Chapter 11. N<sub>2</sub>O Emissions from Managed Soils, and CO<sub>2</sub> Emissions from Lime and Urea Application. <http://www.ipcc-ggip.iges.or.jp/>. Accessed on 8 August 2007.
- Johnson DE, GW Ward and JJ Ramsey. 1996. Livestock methane: Current emissions and mitigation potential, In: ET Kornegay (eds). *Nutrient management of food animals to enhance and protect the environment*. Lewis Publishers, New York, NY.
- Keller JK, AK Bauers, SD Bridgham, LE Kellogg and CM Iversen. 2006. Nutrient control of microbial carbon cycling along an ombrotrophic-minerotrophic peatland gradient. *J Geophys Res* 111, G03006, doi:10.1029/2005JG000152.
- Khan SA, RL Mulvaney, TR Ellsworth and CW Boast. 2007. The myth of nitrogen fertilization for soil carbon sequestration. *J Environ Qual*: 36:1821-1832.
- Kowalenko CG, KC Ivarson and DR Cameron. 1978. Effect of moisture content, temperature and nitrogen fertilization on carbon dioxide evolution from field soils. *Soil Biol Biochem* 10: 417-423.
- Lal R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304: 1623-1626.
- Marwanto S and F Agus. 2013. Is CO<sub>2</sub> flux from oil palm plantations on peatland controlled by soil moisture and/or soil and air temperatures? *Mitig Adapt Strateg Glob Change* 19: 809-819. doi:10.1007/s11027-013-9518-3.
- McLean EO. 1982. Soil pH and lime requirement. In: Page AL, E Baker and R Ellis Jr (eds). *Methods of Soils Analysis*, No. 9, part 2. SSSA, Madison, WI, 199 pp
- Micks P, JD Aber, RD Boone and EA Davidson. 2004. Short-term soil respiration and nitrogen immobilization response to nitrogen applications in control and nitrogen-enriched temperate forests. *For Ecol Manage.* 196: 57-70
- Nagano H, S Kato, S Ohkubo and K Inubushi. 2012: Emissions of carbon dioxide, methane, and nitrous oxide from short- and long-term organic farming Andosols in central Japan. *Soil Sci Plant Nutr* 58: 793-801. doi:10.1080/00380768.2012.739550.
- Nelson DW and LE Sommers. 1982. Total carbon, organic carbon, and organic matter. In: AL Page (ed) *Methods of Soil Analysis*, part 2, 2nd ed. Agronomy 9, Am Soc of Agron Madison, WI, pp. 961-1010.
- Parish F, A Sirin, A Charman, H Joosten, T Minaeva and M Silvius. 2007. *Assessment of peatlands, biodiversity and climate change*. Global Environment Centre, Kuala Lumpur, Malaysia, and Wetlands International, Wageningen, The Netherlands.
- Paustian K, HP Collins and EA Paul. 1997. Management controls on soil carbon. In: EA Paul, K Paustian, ET Elliot and CV Cole (eds). *Soil Organic Matter in Temperate Agroecosystems*, CRC. Press, Inc. pp. 15-49.
- Paustian K, WJ Parton and J Persson. 1992. Modeling soil organic matter in organic amended and N fertilized long term plots. *Soil Sci Soc Am J* 56: 476-488.
- PEACE. 2007. *Indonesia and climate change: Current status and policies*. The World Bank, Department for International Development of Indonesia.
- Sabiham S. 2010. Properties of Indonesian Peat in Relation to the Chemistry of Carbon Emission. *Proceeding of International Workshop on Evaluation and Sustainable Management of Soil Carbon Sequestration in Asian Countries*. Bogor, Indonesia pp. 28-29.
- Sakata R, S Shimada, H Arai, N Yoshioka, R Yoshioka, H Aoki, N Kimoto, A Sakamoto, L Melling and Kinubushi. 2015. Effect of soil types and nitrogen fertilizer on nitrous oxide and carbon dioxide emissions in oil palm plantations, *Soil Sci Plant Nutr* 61: 48-60. doi: 10.1080/00380768.2014.960355.
- Shlegel AJ, KC Dhuyvetter and JL Havlin. 1996. Economic and environmental impacts of long term nitrogen and phosphorus fertilization. *J Produc Agric* 9: 114-118.
- Snyder CS, TW Bruulsema and TL Jensen. 2007. *Greenhouse gas emission from cropping systems and the influence of fertilizer management*. International Plant Nutrition Institute 28: 161-171.



- Stehfest E and AF Bouwman. 2006. N<sub>2</sub>O and NO emissions from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. *Nutr Cycl Agroecosyst* 74: 207-228.
- Uchida Y, I von Rein, H Akiyama and K Yagi. 2013. Contribution of nitrification and denitrification to nitrous oxide emissions in Andosol and from Fluvisol after coated urea application. *Soil Sci Plant Nutr* 59: 46-55. doi:10.1080/00380768.2012.708646.
- Wahyunto and IN Suryadiputra. 2008. *Peatland distribution in Sumatra and Kalimantan-explanation of its data sets including source of information, accuracy, data constraints and gaps*. Wetlands International – Indonesia Programme. Bogor.
- Wilson HM and MM Al-Kaisi. 2008. Crop rotation and nitrogen fertilization effect on soil CO<sub>2</sub> emissions in central Iowa. *Applied Soil Ecology* 39: 264-270.