Carbon dioxide and nitrous oxide emissions associated with tropical peatland degradation

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Abstract
Long term monitoring of CO_2 emission from the peat of natural forest (NF), fire-affected re-growing forest (RF) and cropland (KV) in Plangka Raya, Central Kalimantan, Indonesia has been conducted since 2002. The results showed that the average annual CO_2 emission was 14.8 tC/ha/y in NF, 9.2 tC/ha/y in RF and 25.5 tC/ha/y in KV. The tendency of the CO_2 emission agreed with that of annual peat subsidence. Based on the data of the proportion of peat decomposition and root respiration in CO_2 emission from peat, the value of peat decomposition per unit peat subsidence was estimated to be 4.3 tC/ha/cm in NF, 6.21 tC/ha/cm in RF and 5.91 tC/ha/cm in KV, and peat decomposition to peat subsidence accounted for 46 % in NF, 57 % in RF and 57 % in KV. These results suggest that peatland degradation accelerates peat decomposition. N_2O emission exponentially increased with an increase of peat decomposition. The result of regression analysis using the data of CO_2 emission in tropical peatland compiled by Hooijer *et al*. (2006) together with the data obtained in this study showed that peat decomposition was significantly increased by a fall of the ground water table. The slope of the regression equation for cropland was higher than that for other ecosystems (natural forest, re-growing forest and plantation).

Key Words
CO_2, N_2O, peat decomposition, peat subsidence, ground water table.

Introduction
Indonesia is the country where more than 80% of tropical peat occurs (27Mha). Since 1985, tropical peat swamp forests in the world have been cut for timber production and destroyed widely, along with frequent forest fire. Even now, peat swamp forest is undergoing deforestation at 1.5%/y, to lose 120,000 km^2 (45%) due to clear cut and drainage (Hooijer *et al.* 2006). Among the deforested areas, reclaimed land used for agricultural production is only 30%, and the others are abandoned areas turned into degraded and deforested lands. Tropical peat is composed of woody materials, therefore the peat soils have a relatively high permeability compared with mineral soil or boreal sphagnum peat. Due to this high permeability, a deforested tropical peat dome quickly loses subsurface water from the soil into drainage. The peat soil which loses subsurface water starts to dry, does not allow vegetative recovery and CO_2 emission derived from peat decomposition remarkably increases.

An estimated, total 554 MtC/y CO_2 is released from tropical peatland throughout South East Asia, of which 172 MtC/y is caused by drainage and peat decomposition and 382 MtC/y by burning during peat fire (Hooijer *et al.* 2006). This total amount of CO_2 from peat soil is more than annual CO_2 emission in Japan. It is necessary to note that estimated total CO_2 emission from peat soils due to peat decomposition is based on correlation between ground water table and CO_2 emission, which was created by using 41 data set described in 16 publications. As it is hypothesized that one particular water table is determined by land use across the board, the CO_2 emission estimated in this manner remains uncertaint and unreliable.

In tropical peatland, peat decomposition is one of the factors for peat subsidence. Therefore, measurement of peat subsidence is crucial for predicting CO_2 emission derived from peat decomposition. Peat subsidence occurs due to not only due to peat decomposition but also to shrinkage, compaction and consolidation. Stephens and Stewart (1976) demonstrated that subsidence rate measured in a peat swamp in Florida, USA, increased along with groundwater table depth and soil temperature. Murayama and Bakar (1996) reported that annual peat subsidence in an oil palm plantation area in Peninsula Malaysia ranged from 1.55 to 1.64 cm, of which 52 to 66% was estimated to be due to peat decomposition using 10 tC/ha of annual average CO_2 emission. Wösten *et al*. (1997) estimated that annual CO_2 emission from a cropland in the peatland in Peninsula Malaysia was 27 tC/ha/y, along 2 cm/y peat subsidence, based on the estimation of 60% contribution of peat decomposition to the peat subsidence and 0.1g cm^{-3} bulk density of the peat soil.

However, they also estimated that bulk density of peat soil varied in the range from 0.05 to 0.15 g cm^{-3}. Hence they further estimated that CO_2 emission varied in the range from 13 to 40 tC/ha/y. CO_2 emission from peat land is strongly related to subsidence, ground water table depth, temperature and bulk density of peat. Therefore, a study about the controlling factors of CO_2 emission is required to understand the condition of peatland degradation.
Through the progression of peat decomposition, nitrogen mineralization in peat soil also occurs. This resulting ammonia undergoes nitrification under exposure to oxygen and successive denitrification under anaerobic conditions, leading to N_2O emission. It has been reported that 239 kgN/ha/y of N_2O is emitted from peat soil of arable land in Central Kalimantan, Indonesia (Takakai *et al.* 2006).
Purposes of this study are to estimate relationships between CO_2 emission derived from peat decompositions and subsidence in peatland and to clarify N_2O emission associated with peat decomposition.

Materials and methods

Study sites

Long term monitoring for subsidence and CO_2 and N_2O emissions have been conducted since 2001 at three sites in the peatland of Kalampangan zone near Palangka Raya, Central Kalimantan Indonesia（2˚S, 114˚E）: .1) natural forest influenced by drainage (FT), 2) re-growing forest after forest fire in 1998 and 2002 (RF), and 3) cropland (cultivated since late 1970's) (KV). Peatland of Kalampangan zone is composed of inland dome peat formed in a zone of about 20 km width between Sebangau River and Kahayan River. Around 30 years ago, exploitation started in the zone. After 1996, large scale exploitation proceeded with rice paddy development project under previous Suhatuto administration. However, in 1997/1998 and 2002, large scale peat fires occurred.

CO_2 and N_2O emission

CO_2 and N_2O fluxes from the soil surface have been measured by using a closed-chamber method since 2002. An open bottom cylindrical stainless-steel chamber (18.5-21.0cm in diameter and 25cm in height）was used for the measurement. One day before the measurement, any green vegetation on the measurement plots was cut at ground level and removed. In this case, CO_2 flux consists of CO_2 derived from root respiration and soil organic matter decomposition. In order to measure CO_2 flux derived from only peat decomposition, a root excluded plot of 1m×1m was established. Root-proofing permeable sheet (BKS9812, TOYOBO, Osaka, Japan) was vertically inserted to a depth of more than 30 cm below the ground surface to inhibit re-growth of roots. Flux measurement was conducted at three replicates in cropland and six replicates at other sites. Measurement of CO_2 and N_2O fluxes were conducted according to Takakai *et al*. (2007).
Air temperature at the height of 1m was measured at the same time with gas flux measurements using a thermistor thermometer (CT220, CUSTOM, Tokyo, Japan) for the gas flux calculation.

Subsidence and water table

The water table was measured at the time of gas flux measurement at each site by using a perforated PVC pipe (80 mm diameter and two meter long) with holes of 4 mm diameter opened at the four sides of the pipe every 5 cm interval along the pipe. The PVC pipe was also used for measuring the subsidence. From 2003 in KV, an iron pipe (40 mm diameter) which was vertically inserted from the peat surface to the top of the buried mineral soil layer was used. Subsidence was obtained from the change in the height from the peat surface to top of the pipe measured several times in a year.

Peat soil characteristics

Peat soil samples were taken at every 10 cm interval in each site by using a semi-cylindrical peat sampler (47 mm diameter, 50 cm long). At that time, peat depth was measured by the sampler. Bulk density, total carbon content, organic matter content and ash content were measured at the laboratory.

Results and discussion

CO_2 emission

Cumulative CO_2 emission at each site from April, 2002 to November, 2008 is shown in Figure 1. KV showed largest cumulative CO_2 emission was shown as 164 tC/ha in KV, followed by 97 tC/ha in FT and smallest CO_2 emission of 58 tC/ha in RF. Annual mean CO_2 emission (±SD) was significantly different among the sites which was 14.8 (± 2.8) tC/ha/y in FT, 9.2 (± 2.9) tC/ha/y in RF, and 25.5 (± 7.6) tC/ha/y in KV. The sites with high CO_2 emission showed large subsidence. Annual mean subsidence rate was largest in KV (4.1 cm/y), followed by FT (2.2 cm/y) and smallest in RF (0.9 cm/y).

However, the CO_2 emission from soil includes root respiration and peat decomposition. But, in crop fields, there was no significant difference of CO_2 emissions between root intact and root excluded plots. This indicates that root respiration can be ignored. However, Melling (2005) indicated that there was significant difference of CO_2 emissions between root intact and root excluded plots in a forest, oil palm plantation and sago plantation. The proportion of CO_2 emission from root excluded plot to root intact plot was 66% on average (66 % in forest, 60 % in oil palm plantation and 72 % in sago palm plantation). Using the contribution of peat decomposition to total CO_2 emission (100% in croplands and 66% in other lands), peat decomposition was estimated to be 9.76 tC/ha/y in FT, 6.07 tC/ha/y in RF and 24.0 tC/ha/y in KV (Table 1). The ratio of peat decomposition to peat subsidence was 4.40 tC/ha/cm in FT, 6.77 tC/ha/cm in RF and 6.27 tC/ha/cm in KV. Using the bulk density of top layer and peat C content, the contribution of peat decomposition to peat subsidence (decomposability) was estimated to be 42 % in NF, 62 % in RF and 61 % in KV. This indicates that agriculture and peat fire make the peat more decomposable. Hooijer *et al*. (2006) indicated a positive tendency that the

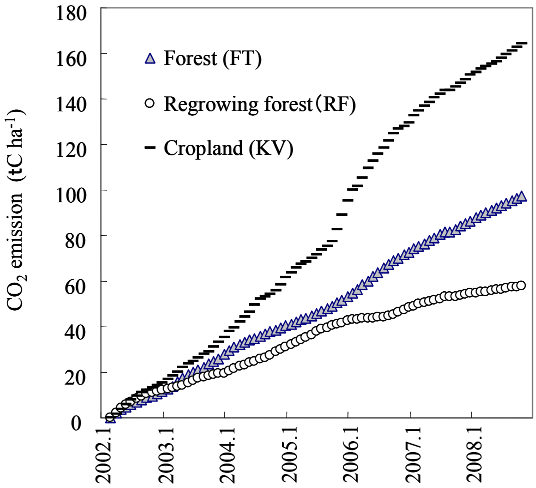

Figure 1. Cumulative CO_2 emission in Central Kalimantan, Indonesia after April 2002.

Table 1. Characteristics of CO_2 emission derived from peat decomposition in Central Kalimantan, Indonesia.

	Decomposition	Subsidence	Decomposition /Subsidence	Ash (0-50cm)		Peat carbon (0-50cm)		Bulk density (0-50cm)	Carbon in top 0-1cm peat layer	Decomposability *
	tC ha^{-1} y^{-1}	cm y^{-1}	tC ha^{-1} cm^{-1}	g kg^{-1}	SD	g kg^{-1}	SD	g cm^{-3}	tC ha^{-1} cm^{-1}	%
Forest(FT)	9.76	2.22	4.40	4.85	0.15	622	29	0.151 [1)]	9.37	47
								0.118 [2)]	7.36	60
								0.183 [3)]	11.38	39
Re-growing forest (RF)	6.07	0.90	6.77	5.15	1.57	611	20	0.180 [1)]	10.98	62
								0.140 [2)]	8.54	79
								0.220 [3)]	13.41	50
Crop land (KV)	25.49	4.07	6.27	5.91	1.50	604	3	0.170 [1)]	10.28	61
								0.125 [2)]	7.57	83
								0.215 [3)]	12.98	48

1)Average bulk density, 2)Bulk density -SD, 3) Bulk density +SD;
* (Decomposition /Subsidence) / (Carbon in top 0-1cm peat layer)

CO_2 emission increased with fall of ground water table. Regression analysis for the relationship between peat decomposition and ground water table depth was conducted using the data compiled by Hooijer *et al.* (2006) together with the data obtained in this study. The results revealed that peat decomposition was significantly correlated to ground water table depth for the data set dived into two groups, land with woody vegetation (P<0.01) and without woody vegetation (P<0.01). The slope of the regression equation for the land without woody vegetation was higher than that for the land with woody vegetation. This indicates that peat soils in cropland are more decomposable than in forests (Figure 2). Murayama and Bakar (1996) showed that for peat decomposition increased with

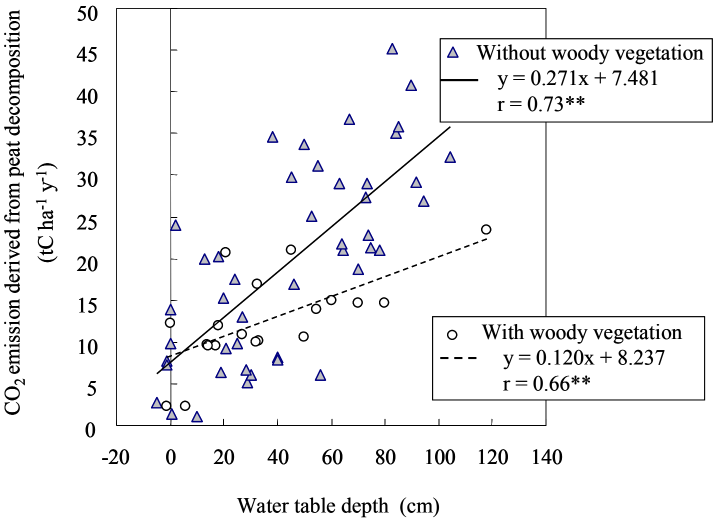

Figure 2. Relationship between annual mean water table depth and CO_2 emission derived from peat decomposition.

increase of soil pH and ash content of peat. Ash contents were highest KV and smallest in FT (Table 1). Farmers ordinarily apply ash to their fields in order to increase base cation content and soil pH of ombrotrophic acidic tropical peat soils, and peat fire supplies ash. These activities may stimulate peat decomposition.

N_2O emission

There was a significant exponential relationship between N_2O emission and peat decomposition ($P<0.01$) (Figure 3). The data includes previously reported values measured in a forest, oil palm plantation, sago palm plantation in Sarawaku, Malaysia (Melling *et al.* 2005; Melling *et al.* 2007). There was a large scatter in the relationship and there was a very wide range of N_2O emissions (from 0.04 to 4.39 kg N/ha/y in forests, re-growing forest and plantation and from 5.78 to 679 kgN/ha/y in croplands). Cropland enhanced N_2O emission significantly. Takakai *et al.* (2006) showed that annual N_2O emission increased with an increase of annual precipitation and N_2O was emitted proportionally to NO_3-N content in peat soil when peat soil became wet during the period of rainy season. This suggests that the N_2O was produced through denitrification in rainy the season using NO_3-N accumulated in peat soil through nitrification after mineralization of N released with peat decomposition in the dry season. Peat decomposition can involve heterotrophic respiration using both O_2 molecule and oxygen contained in NO_3^-(Hashidoko *et al.* 2007). Therefore, the large scatter in the relationship between N_2O and CO_2 emission is ascribed mainly to variation of nitrification and denitrification activities in soil which are influenced by the soil moisture condition and nitrate content

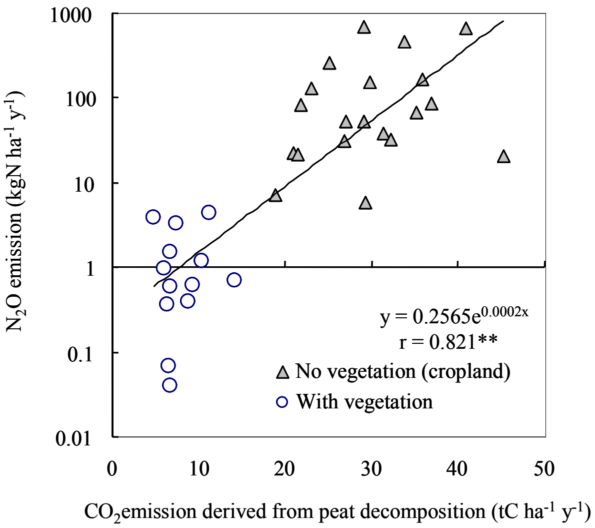

Figure 3. Relationship between CO_2 emission and N_2O emission

Conclusions

The fall of ground water table depth associated with drainage and agricultural land use in peatlands triggers the increase of peat decomposition. The higher decomposability of cropland peat might be caused by an increase in ash content of the peat soil. N_2O emission was also higher in cropland during the rainy season due to the high activity of denitrification.

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