# EFFECTS OF SELECTIVE LOGGING AND APPLICATION OF PHOSPHORUS AND NITROGEN ON FLUXES OF CO<sub>2</sub>, CH<sub>4</sub> AND N<sub>2</sub>O IN LOWLAND TROPICAL RAINFORESTS OF BORNEO

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We compared fluxes of carbon dioxide ( $CO_2$ ), nitrous oxide ( $N_2O$ ) and methane ( $CH_4$ ) in a primary forest and a secondary forest that has experienced selective logging more than 14 years ago. Effects of phosphorus (P) and nitrogen (N) application were also reported. We observed lower CO<sub>2</sub> fluxes in the logged forest (2.0–2.4 g carbon (C)  $m^2 day^1$ ) than the primary forest (2.4–3.5 g C  $m^2 day^1$ ). The lower fluxes were probably because root respiration and heterotrophic respiration were lower in the logged forest. Smaller amounts of microbial biomass C (840-985 and 589-641 µg C g soil<sup>-1</sup> in the primary and secondary forests respectively) and N (109-143 and 106-117 µg N g soil<sup>-1</sup>) in the secondary forest than the primary forest suggested that there were less substrate inputs such as leaf and root litters, soil organic matters and root exudates in the former which produced less microbial population with lower heterotrophic respiration. Application of P increased CO<sub>2</sub> emission (from 2.0-2.7 to 2.2-3.5 g C m<sup>2</sup> day<sup>1</sup>) and microbial biomass N (from 106-115 to 110-143 µg N g soil<sup>-1</sup>), suggesting that the belowground ecosystems of both forests were limited by availability of P as reported in other tropical forests. Fluxes of CH<sub>4</sub> showed no differences between forests or manipulation of nutrient because of the high variability of fluxes. Logging operation and nutrient application did not influence N<sub>2</sub>O fluxes. The invariable N<sub>2</sub>O fluxes occurred because water content was low during sampling and emission of N<sub>9</sub>O was restricted by water availability, which might have masked the effects of logging or nutrient application on N<sub>2</sub>O emission.

Keywords: Logged forest, primary forest, secondary forest, microbial biomass

### **INTRODUCTION**

A large part of the remaining forests in South-East Asia consists of degraded or logged over forests due to clear cutting or selective logging (ITTO 2006). In Malaysia, for example, more than 10.7 million ha of forests are classified as production forests (ITTO 2011), which account for more than half of its total forest area. Logging causes extensive forest degradation and negative impacts on ecosystem services such as carbon (C) storage, protection of hill slopes and moderation of microclimate. Efforts have been made to reduce logging intensity and collateral damages on ecological functions (Putz et al. 2008, ITTO 2011, Kitayama 2013).

Logging has great impacts on fluxes of greenhouse gases, namely, carbon dioxide  $(CO_2)$ , nitrous oxide  $(N_2O)$  and methane  $(CH_4)$  (Tate et al. 2006, Yashiro et al. 2008, Page et al. 2011). Logging can either enhance or reduce

 $CO_2$  emission (Hendrickson & Robinson 1984, Nakane et al. 1986, Lavoie et al. 2013, Zerva & Mencuccini 2005, Köster et al. 2011, Goutal et al. 2012). In contrast, N<sub>2</sub>O and CH<sub>4</sub> fluxes are usually enhanced by logging operation (Yashiro et al. 2008, Page et al. 2011). Factors that control fluxes after logging include soil/air temperature, moisture, organic matter inputs and soil nitrogen (N) cycling (Ishizuka et al. 2002, Zerva & Mencuccini 2005, Yashiro et al. 2008, Page et al. 2011). The fluxes gradually return to background levels within a few months to a few years after logging (Tang et al. 2005, Page et al. 2011), but observations of more than 10 years after logging of tropical forests are still rare.

Primary productivity in many tropical forests is limited by phosphorus (P) shortage (Vitousek & Sanford 1986, Elser et al. 2007) in contrast to that of temperate forests which are usually limited by N. Soil microbial activities in tropical forests are also believed to be limited by availability of P, because soil heterotrophic microbial respiration (Cleveland et al. 2002, Ilstedt et al. 2003, Cleveland & Townsend 2006, Liu et al. 2012, Mori et al. 2013c) or biomass (Liu et al. 2012, 2015, Mori et al. 2016) is increased by addition of P. Since CH<sub>4</sub> and N<sub>2</sub>O exchange between the atmosphere and soil is also derived from soil microbial activities, P availability may also control CH<sub>4</sub> uptake and N<sub>2</sub>O emission in P-limited tropical forest soil (Mori et al. 2010b). Application of P in a natural tropical forest stimulates root N uptake and reduces N inhibition on CH<sub>4</sub> oxidation, increasing the CH<sub>4</sub> uptake rates (Zhang et al. 2011). In a series of studies in a tropical leguminous tree plantation, P application reduced N<sub>2</sub>O emission by stimulating root uptake of N resources (Mori et al. 2014) or soil water (Mori et al. 2013b) but stimulated the emission in laboratory by accelerating microbial nitrification and denitrification (Mori et al. 2010a, 2013d). However, studies of the effects of P addition on fluxes of CH<sub>4</sub> and N<sub>9</sub>O are biased to plantations (Mori et al. 2013a, Zhang et al. 2014), laboratory (Mori et al. 2010a), paddy fields (Adhya et al. 1997, Lu et al. 1999) or secondary forests (Wang et al. 2014). Very few studies have tested the effects of P addition in natural tropical lowland forests.

In 2011, a nutrient application experiment was carried out using P and N in two types of mixed dipterocarp tropical rainforests (one is primary forest and the other is secondary forest which has experienced selective logging more than 14 years ago) in Sabah, Malaysia. These experimental sites provided a chance to test the effects of logging (long-term influence) and nutrient (P and N) application on greenhouse gas fluxes. In this study, we tested the effects of selective logging and nutrient application on fluxes of  $CO_2$ ,  $CH_4$  and  $N_2O$  in tropical lowland forests in Sabah.

# MATERIALS AND METHODS

# **Study sites**

Study sites are located in a primary forest in Deramakot Forest Reserve (551 km<sup>2</sup>) and in a selectively logged forest in Tangkulap Forest Reserve (275 km<sup>2</sup>) in Sabah, Malaysia (5° 14–30' N, 117° 11–36' E) (Imai et al. 2010). The climate is humid equatorial. Mean annual temperature was 25.2 °C with annual precipitation of 3098 mm for the period 2008–2010 (Ong et al. 2013). Both forests are mixed dipterocarp tropical rainforests located adjacent to each other (Imai et al. 2012). Logging in Tangkulap started in 1970s, thereafter the forest was damaged due to repeated conventional logging until 2001 (Imai et al. 2009).

#### **Fertilisation experiment**

Twelve 0.12-ha (30 m × 40 m) plots were established in each forest and experimental nutrient manipulations were conducted in both forests. Treatments included control (without P or N application), P-application, N-application, and PN-application (n = 3 for each treatment). In December 2011, triple super phosphate and urea were applied by hand at a rate of 50 kg P ha<sup>-1</sup> and 100 kg N ha<sup>-1</sup> respectively. To ensure uniform application, fertiliser was scattered over 12 areas, each measuring 10 m × 10 m (0.12-ha plot divided into 12 parts). Thereafter, nutrient application was conducted at the same rate once a year.

#### Gas flux measurements

In March 2015, CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O fluxes were measured using static chamber method (Ishizuka et al. 2002). We set four PVC chambers (7.7 cm diameter, 15 cm height) in each plot (n = 12 for each treatment). The chambers were covered with lids equipped with sampling ports in the middle and silicone seats at adhesive surfaces. Chambers and the lids were attached using four eyeball clips so as not to release air. During daytime, 15-mL gas samples were taken at 0 and 30 min after the closure of the lids and transferred into 10-mL pre-evacuated glass vials equipped with butyl rubber stoppers. Due to time, physical and labour constraints in taking many samples, only two gas samples (0 and 30 min) were taken for each flux measurement. This might have underestimated gas fluxes if gas concentration inside the chamber did not change linearly over time due to high fluxes exceeding maximum measurement. Since changes in gas concentrations were linear for the first 30 min even when the range of fluxes was larger than the present study (Konda et al. 2008), we believed that the gas fluxes were properly determined. Gas concentrations were analysed

using gas chromatograph equipped with thermal conductivity detector for  $CO_2$ , flame ionisation detector for  $CH_4$  and electron capture detector for N<sub>2</sub>O. Gas fluxes were calculated as follows:

$$\mathbf{F} = \boldsymbol{\rho} \times (\mathbf{V}/\mathbf{A}) \times (\Delta \mathbf{c}/\Delta \mathbf{t}) \times [273/(\mathbf{T} + 273)] (1)$$

where F = gas flux (mg m<sup>-2</sup> hour<sup>-1</sup>),  $\rho$  = density of gas (kg m<sup>-3</sup>), V = volume of the chamber (m<sup>3</sup>), A = base area of the chamber (m<sup>2</sup>),  $\Delta c / \Delta t$  = change of concentration with time (ppmv hour<sup>-1</sup>) and T = temperature (°C) in the chamber.

#### Soil analyses

Two soil cores were taken at a depth of 0–5 cm approximately 50 cm apart from each chamber using a soil sampling core (3.4 cm diameter) to make a composite (in total 12 composite samples in each treatment). After roots and organic matters were removed, soil samples were passed through a 2-mm sieve. Water-filled pore space (WFPS) was calculated as follows:

WFPS (%) = 
$$\omega \times BD/(1 - BD/PD)$$
 (2)

where  $\omega$  = gravimetric water content of soil (g g<sup>-1</sup>), BD = bulk density (mg cm<sup>-3</sup>) and PD = particle density (2.65 mg cm<sup>-3</sup>, a generally used typical value (Rossi et al. 2008)). Inorganic N (NH<sub>4</sub> and NO<sub>3</sub><sup>-</sup>) and dissolved organic C in the soil were extracted by shaking 1 fresh soil: 5 K<sub>2</sub>SO<sub>4</sub> (0.5 M) for 30 min using electric shaker NH<sub>4</sub><sup>+</sup> was determined by indophenol blue absorptiometry and NO<sub>3</sub><sup>-</sup> by the naphthyl ethylenediamine method using flow-injection analyser. Dissolved organic C was analysed using total organic C analyser. Soil microbial biomass C and N were determined using chloroform fumigation extraction method (Vance & Jenkinson 1987).

#### Statistical analysis

Three-way ANOVA followed by Tukey's hoc test (primary forest vs logged forest, without N vs N, without P vs P) was used for comparing each gas type and soil chemical data, assuming the normality of data. If interactions were significant, simple main effect analyses (Tukey) were performed. We assumed N<sub>2</sub>O fluxes were higher than zero, thus replaced data lower than zero with zero. All statistical analyses were performed by Excel 2013 with statistical add-in software (SSRI).

#### Results

During the present research, water-filled pore space was low in every site (Table 1).  $CO_2$ fluxes were significantly lower in the logged forest (mean daily fluxes of 2.0, 2.2, 2.3 and 2.6 g C m<sup>-2</sup> day<sup>-1</sup> in control, P-, N- and PN-applied plots respectively, Figure 1a) than the primary forest (2.7, 3.1, 2.4, 3.5 g C m<sup>-2</sup> day<sup>-1</sup> respectively). Application of P significantly increased CO<sub>2</sub> emission without any interaction with logging nor N application, while N application did not influence CO<sub>2</sub> emission (Figure 1a). N<sub>2</sub>O and CH<sub>4</sub> fluxes were not influenced by logging operation, P nor N application (Figure 1b and c). Microbial biomass C and N values were significantly higher in the primary forest than in the logged forest (Figure 2). Application of P significantly increased microbial biomass N, but not microbial biomass C. Microbial biomass C and N values were not affected by addition of N. Logging operation and nutrient application affected properties of soil C and N. Dissolved organic C contents were higher in the primary forest than the logged forest, but not influenced by nutrient application (Table 2). Soil NH<sub>4</sub><sup>+</sup> contents were increased by N but not affected by logging nor P application (Table 2). Logging and nutrient application significantly influenced soil  $NO_3^-$  contents (Table 2). Applications of N and P increased  $NO_3^-$  contents only in the primary forest (Table 2).

#### DISCUSSION

#### Effects of logging on CO<sub>2</sub> emission

CO<sub>2</sub> fluxes from the primary forest ranged from 2.4 to  $3.5 \text{ g C m}^{-2}$  day<sup>-1</sup>, which were comparative with other tropical lowland forests  $(1.4-4.4 \text{ g m}^2 \text{ day}^1)$ (Fernandes et al. 2002, Ishizuka et al. 2002, Kiese & Butterbach-Bahl 2002, Schwendenmann et al. 2003, Dalal & Allen 2008, Yashiro et al. 2008). Logging can either increase or decrease  $CO_2$ emission in forests. Emission of CO<sub>2</sub> is increased when soil/air temperature (Yashiro et al. 2008), soil moisture (Page et al. 2011) and organic matters (e.g. logging slash and dead roots) (Tate et al. 2006) increase. On the other hand, decrease in root respiration, substrate inputs (such as leaf and root litters) and microbial population can reduce CO<sub>2</sub> emission (Hendrickson & Robinson 1984, Schilling et al. 1999, Zerva & Mencuccini 2005, Page et al. 2011). Time after logging has



Figure 1 Fluxes of (a)  $CO_2$ , (b)  $N_2O$ , and (c)  $CH_4$ under different treatment in a primary forest and a logged forest; P = phosphorus, N = nitrogen; data are illustrated as means and error bars represent 1 standard deviation, n = 12 (n = 11 in  $CO_2$  and  $CH_4$ fluxes at PN treatment in the primary forest, and n = 11 in  $CO_2$  fluxes at PN treatment in the logged forest because of the experimental failure)



Figure 2 Microbial biomass (a) carbon and (b) nitrogen under different treatment in a primary forest and a logged forest;
P = phosphorus, N = nitrogen, MBC = microbial biomass carbon, MBN = microbial biomass nitrogen; data are illustrated as means, and error bars represent 1 standard deviation, n = 12

great impacts on soil respiratory response (CO<sub>2</sub> emission) with an initial increase in CO<sub>2</sub> emission due to increased substrate availability through harvest slash inputs followed by gradual decrease as tree roots gradually die and stop respiring (Guo et al. 2010, Page et al. 2011). Lower CO<sub>2</sub> emission observed in the logged forest (2.0–2.6 g C m<sup>-2</sup> day<sup>1</sup>; Figure 1a) compared with the primary forest (2.4–3.5 g C m<sup>-2</sup> day<sup>1</sup>, Figure 1a) are in accordance with previous findings, because the stimulatory effects of logging operation on CO<sub>2</sub> emission have disappeared after 14 years. Lower CO<sub>2</sub> emission in the logged forest could

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Forest type		Air temperature (°C)		Soil temperature (°C)		WFPS (%)	
		Average	SD	Average	SD	Average	SD
Primary forest	Control	26.0	1.7	24.7	0.4	25.3	2.4
	Ν	25.7	0.7	24.5	0.2	24.6	4.1
	Р	26.3	0.7	24.5	0.2	30.9	8.5
	NP	26.0	1.1	24.8	0.3	28.5	4.1
Logged forest	Control	25.8	1.3	25.0	0.3	36.3	7.8
	Ν	27.5	0.4	25.4	0.3	30.1	5.2
	Р	26.6	2.2	25.1	0.3	30.1	4.0
	NP	26.9	1.6	25.3	0.3	33.7	4.3

 Table 1
 Environmental parameters during sampling

SD = standard deviation; WFPS = water filled pore space, P = phosphorus, N = nitrogen

be attributed to lower root respiration and substrates for heterotrophic respiration such as leaf and root litters, soil organic matters and root exudates. Microbial biomass C and N were lower in the logged forest than in the primary forest (Figure 2). Decrease in substrate inputs into the soil could have reduced microbial population (Schilling et al. 1999, Zerva & Mencuccini 2005), decreasing heterotrophic respiration (CO<sub>2</sub> emission). In contrast with microbial biomass, dissolved organic C contents were higher in the logged forest than in the primary forest (Table 2). Although dissolved organic C is thought to be a substrate for microbial respiration, the rate of its production rather than its concentration was suggested to be the limiting factor for soil respiration rates (Bengtson & Bengtsson 2007). It is assumed that the turnover of dissolved organic C is faster in primary than in logged forests.

# Effects of logging on fluxes of CH<sub>4</sub> and N<sub>2</sub>O

The CH<sub>4</sub> flux values were comparable with other tropical rainforests (Potter et al. 1996 (0.78 mg C m<sup>-2</sup> day<sup>-1</sup>), Dalal & Allen 2008 (1.1 mg C m<sup>-2</sup> day<sup>-1</sup>)). Logging causes reduction in CH<sub>4</sub> uptake due to soil compaction and increase in soil moisture, temperature or accelerated N cycles (Zerva & Mencuccini 2005). On the contrary, this study demonstrated that CH<sub>4</sub> fluxes in the forest logged more than 14 years ago showed no significant differences with those in the primary forest. The negative effects of logging on CH<sub>4</sub> uptake might have disappeared as the forests and CH<sub>4</sub>-oxidising microbes therein recovered.

Emission rates of  $N_2O$  (Figure 1b) in the logged and primary forests were at the lower end of the tropical forest average (0.23–3.5 mg N m<sup>-2</sup> day<sup>-1</sup>; Dalal & Allen 2008), most possibly due to lower water-filled pore spaces (Table 1). The fact that higher inorganic N in N-applied plots did not result in higher N<sub>2</sub>O fluxes supported this idea (Figure 1, Table 2). Another possible reason is that tropical forests in Asia have fewer legumes (Primack & Corlett 2005) (also in our study site) compared with neotropical (Steege et al. 2000) and African tropical (Schulze et al. 1991) forests and N cycling is slower (Arai et al. 2008). Emission of N<sub>2</sub>O from Asian tropical forests was lower than from the other areas (Ishizuka et al. 2002).

Although logging operation generally stimulated  $N_2O$  emission through increases in N cycling (Tate et al. 2006, Page et al. 2011), this was not observed in this study. There were no differences in  $N_2O$  emission between logged and primary forests (Table 2). Inorganic N pools were also not affected by logging operation. The impact of logging on  $N_2O$  emission may have disappeared during the long term of recovery. However, it is also possible that low water-filled pore space, one of the most important factor controlling  $N_2O$  emission, has masked the impact of logging on  $N_2O$  emission.

# Effects of nutrient addition on greenhouse gas emission

Application of P significantly increased  $CO_2$ emission (Figure 1a), suggesting that P availability limited the belowground ecosystems in tropical

Forest type		DOC µg C g soil <sup>-1</sup>		$\mathrm{NH_4^+}$ µg N g soil <sup>-1</sup>		NO <sub>3</sub> - μg N g soil <sup>-1</sup>	
		Average	SD	Average	SD	Average	SD
Primary forest	Control	205	29	22	6.4	2.2	1.7
	Ν	207	40	117	151	9.7	7.6
	Р	211	33	22	6.6	8.1	5.0
	NP	212	35	151	185	16	5.9
Logged forest	Con.	238	58	19	3.4	7.7	4.4
	Ν	246	39	117	135	11	9.0
	Р	225	23	19	3.6	3.7	2.2
	NP	217	26	74	70	4.6	3.6
Significant factors (p < 0.05, three-way ANOVA)		Forest		Ν		Forest N	
						Forest × P	
						$\textit{Forest} \times \textit{N}$	

 Table 2
 Labile carbon and nitrogen contents under different nutrient treatments in primary and logged forests

DOC = dissolved organic carbon, P = phosphorus, N = nitrogen, C = carbon; SD = standard deviation

forests (Cleveland et al. 2002, Cleveland & Townsend 2006, Liu et al. 2012). Shortage of P in belowground was relieved by P application, leading to stimulated root respiration (Mori et al. 2013e) and accelerated decomposition of organic matters by heterotrophic microbes (Cleveland et al. 2002, Ilstedt et al. 2003). On the other hand, P application did not change the amount of microbial biomass C, although microbial biomass N was increased by P application (Table 2). This could be due to the microbial community shift affected by P application in P-limited soils (Liu et al. 2012). Higher emission of CO<sub>2</sub> and microbial biomass N contents might be partly affected by higher water-filled pore space condition in P-applied plots in the primary forest (Table 1). Although N addition did not change  $CO_{2}$ emission (Figure 1a), we cannot conclude that the ecosystem was not limited by N. This is because when N is limited, its addition reduces decomposition of organic matters, which is known as N-mining (Moorhead & Sinsabaugh 2006).

The effects of P application on  $CH_4$  fluxes have been well studied in laboratory experiments, paddy fields and plantations but the results are inconsistent. Phosphorus influences microbial methanotrophic and methanogenesis activity directly or indirectly through changing the amount of root exudates and root uptake of water and N (Lu et al. 1999, Zhang et al. 2011). Very few reports have investigated the effects of P on CH<sub>4</sub> fluxes in natural tropical forests. Application of P stimulated root N uptake and mitigated N inhibition on CH<sub>4</sub> uptake in a natural tropical forest in China (Zhang et al. 2011). However, we did not observe any differences between sites with or without P application. Application of N inhibits CH<sub>4</sub> oxidation through enzyme inhibition by NH<sub>4</sub><sup>+</sup>, NO<sub>2</sub><sup>-</sup> toxicity and osmotic stress (Schnell & King 1994, Kravchenko et al. 2002, Baggs & Blum 2004, Bodelier & Laanbroek 2004). However, this was not the case in the present study. Application of N did not affect CH<sub>4</sub> fluxes.

Application of P suppressed N<sub>2</sub>O emission through stimulating N uptake of roots and reduced resources (N) producing N<sub>2</sub>O in P-limited maize cropland (Baral et al. 2014), tropical monoculture plantation (Mori et al. 2013b, 2014) and N-saturated natural forest (Chen et al. 2015). Phosphorus application stimulated N<sub>2</sub>O emission if vegetation was excluded (Mori et al. 2010a, 2013d). Thus, P application in P-limited ecosystem influences emission of N<sub>2</sub>O. However, in the present study, P application had no significant effect on N<sub>2</sub>O emission probably because of low water-filled pore space. Similarly, N application, which generally increased N<sub>2</sub>O emission in most other studies (Liu & Greaver 2009), was also not significant in the present study (Figure 1), suggesting that water (and not N resources) limited N<sub>2</sub>O production. Dry conditions may have masked the effects of P and N application on N<sub>2</sub>O emission in the present study.

# CONCLUSIONS

The effects of logging on the emission of soil  $CO_2$ were still discernible 14 years after the operation has ceased, but fluxes of  $N_2O$  and  $CH_4$  were not affected. Availability of P limited belowground ecosystem including root respiration and microbial activities. In contrast to the hypothesis that P application influenced  $N_2O$  and  $CH_4$  fluxes in P-limited tropical forests, significant effects of P application were not observed in the present study.

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