FIELD NOTE

A preliminary report: does reduced impact logging (RIL) mitigate non-CO\textsubscript{2} greenhouse gas emissions from natural production forests?

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ABSTRACT  Reduced impact logging (RIL) is a challenge to mitigate detrimental effects of selective logging, which is known to mitigate C losses as timbers and forest degradation. Although it was predicted that RIL can also mitigate non-CO\textsubscript{2} greenhouse gas fluxes through reduced disturbances, the reality has been rarely reported. In the present study, we conducted a preliminary research on N\textsubscript{2}O and CH\textsubscript{4} fluxes in a 2-ha plot in each of primary, RIL and conventional logging (CL) forest in Bornean lowland tropical rain forests. The results showed that CL significantly enhanced N\textsubscript{2}O emissions, but N\textsubscript{2}O emissions from the RIL forest did not differ from those from the primary forest, suggesting that RIL can mitigate N\textsubscript{2}O emissions enhanced by CL. On the other hand, CH\textsubscript{4} fluxes were not significantly different among three forest types.

Key words: conventional logging, methane, nitrous oxide, reduced impact logging, tropical rain forest

INTRODUCTION

Unregulated selective logging and clear cutting have degraded most of the natural forests in tropical Asia (ITTO 2006; Kitayama 2013; Burivalova et al. 2014), largely contributing to anthropogenic carbon (C) emissions (Schrope 2009; van der Werf et al. 2009). Reduced-impact logging (RIL) is an option to mitigate the detrimental impacts of selective logging on natural production forests (Lagan et al. 2007; Putz et al. 2008). RIL consists of careful pre-harvest planning, improved harvesting techniques, and reduced harvest and post-harvest silvicultural treatments (Kleine and Heuveldop 1993; Lagan et al. 2007; Putz et al. 2008). It was shown that RIL mitigated losses of C storage (Imai et al. 2009) compared with conventional logging (CL). In addition, RIL successfully mitigated the shifts in community composition of trees (Imai et al. 2012b) and soil animals (Hasegawa et al. 2014) which were caused by forest degradation.

It is well documented that logging operation enhanced non-CO\textsubscript{2} greenhouse gas fluxes, i.e., stimulated N\textsubscript{2}O emissions and reduced CH\textsubscript{4} uptakes (Steudler et al. 1991; Bradford et al. 2000; Castro et al. 2000; Yashiro et al. 2008; Page et al. 2011; Wu et al. 2011). These elevated gas fluxes were attributed to increases in soil/air temperature, soil moisture, organic matter inputs, and soil N cycling (Ewel et al. 1981; Steudler et al. 1991; Ishizuka et al. 2002; Zerva and Mencuccini 2005; Yashiro et al. 2008; Page et al. 2011; Hosea et al. 2014), which were caused by logging operations. Although it was predicted that RIL can mitigate the gas fluxes through reduced disturbances (Keller et al. 2005), to our knowledge, no studies have compared the non-CO\textsubscript{2} greenhouse gas fluxes in the RIL forests with the CL forests. In this paper, we report a preliminary research on N\textsubscript{2}O and CH\textsubscript{4} fluxes in a 2-ha plot in each of the primary, RIL and CL forest in Bornean lowland tropical rain forests. We hypothesized that (i) CL stimulates N\textsubscript{2}O emissions and reduces CH\textsubscript{4} uptakes (increases non-CO\textsubscript{2} greenhouse gas fluxes), and (ii) RIL mitigates the increases in non-CO\textsubscript{2} greenhouse gas fluxes.
MATERIALS AND METHODS

Study sites

Study sites were located in Deramakot Forest Reserve and Tangkulap Forest Reserve in Sabah, Malaysia (5°14′-30′ N, 117°11′-36′ E). Both forests are mixed dipterocarp tropical rain forests and located adjacent to each other (Imai et al. 2012a). The climate is humid equatorial, with little seasonal variation. The mean annual temperature was 25.2°C and the annual precipitation was 3,098 mm for the period 2008-2010 (Ong et al. 2013).

Forests in Deramakot and Tangkulap were licensed for logging in 1956 and 1970, respectively. Thereafter, forests in Tangkulap got damaged by repeated CL until 2001 (Imai et al. 2009). On the other hand, in 1989, Deramakot was chosen by the Sabah State Government as a model site to develop a sustainable forest-management system and all logging activities were suspended thereafter (Imai et al. 2012b). In 1995, a new management system with RIL started (Lagan et al. 2007) in Deramakot.

Plot settings

During November 2006-February 2008, three 2-ha (200 m × 100 m) plots were established in a primary, a RIL, and a CL forest (Imai et al. 2012b). In Deramakot, the plot in a primary forest was established in the conservation area. We also established the RIL plot in a forest logged by RIL during 1995-2000. The CL plot was established in Tangkulap. According to the observation of Landsat scenes, both of the RIL and CL forests were logged during the similar period (Imai et al. 2012b).

Gas flux measurements

In January 2016, N₂O, CH₄, and CO₂ fluxes were measured by using the static chamber method (Ishizuka et al. 2005; Mori et al. 2013). In the present preliminary study, we determined the gas fluxes only once, partly due to the hard access to the research site. However, it would be possible to compare the sizes of gas fluxes among different types of forests (primary, RIL, and CL) by the single gas measurement, because this region has little seasonal climate variation (Imai et al. 2012b), which is one of the most important factors controlling gas flux variation (Kiese et al. 2003; Konda et al. 2010), and the size relation of gas fluxes among the three types of forests would be less affected by the sampling frequency. Sixteen PVC chambers (7.7 cm diameter, 15 cm height) were set in each plot. The chambers were covered with lids equipped with silicon seat at adhesive surface and sampling ports on the middle of the lids. The chambers and the lids were attached by using four eyeball clips so as not to release the air. Fourteen-mL gas samples were taken by a syringe at 0, 20, and 40 min after the closure of the lids and transferred into 10-mL pre-evacuated glass vials equipped with butyl rubber stoppers. We collected gas samples during day-time. Gas concentrations were analyzed using a gas chromatograph (GC-14B; Shimadzu, Kyoto, Japan) equipped with an electron capture detector for N₂O, a flame ionization detector for CH₄, and a thermal conductivity detector for CO₂. Gas fluxes were calculated as follows:

\[ F = \rho \times (V/A) \times \left( \frac{\Delta c}{\Delta t} \right) \times \left[ \frac{273}{(T + 273)} \right] \]  

where F is the gas flux (mg m⁻² h⁻¹); ρ is the density of gas (kg m⁻³); V is the volume of the chamber (m³); A is the base area of the chamber (m²); \( \Delta c/\Delta t \) is the change of concentration with time (ppmv h⁻¹) and T is the temperature (°C) in the chamber.

Soil analyses

We took soil samples (0-5 cm) nearby each chamber, using a soil sampling core (3.4 cm diameter). Soil samples were passed through a 2-mm sieve to remove roots and large organic matters. Water-filled pore space (WFPS) was calculated as follows:

\[ \text{WFPS} (%) = \omega \times \frac{BD}{1 - BD/PD}, \]  

where \( \omega \) (g g⁻¹) is the gravimetric water content of soil, BD (mg cm⁻³) is the bulk density (data from Imai et al. (2010) for Deramakot and Aoyagi et al. (2013) for Tangkurap), and PD is the particle density (2.65 mg cm⁻³, a generally-used typical value (Rossi et al. 2008)). Inorganic N (NH₄⁺ and NO₃⁻), dissolved organic carbon (DOC), and dissolved N (DN) in the soil were extracted by shaking fresh soil and 0.5 M K₂SO₄ with 1:5 ratio for 30 min. NH₄⁺ was determined by indophenol blue absorptiometry, and NO₃⁻ by the naphthyl ethylenediamine method using a flow-injection analyzer (AQLA-700-NO, Aqualab, Tokyo, Japan). Dissolved organic N (DON) was calculated by subtracting inorganic N from DN. DOC and DN were analyzed by a total organic carbon analyzer with a total flow-injection analyzer (AQLA-700-TOC, Shimadzu, Kyoto, Japan). Soil microbial biomass C and N were determined by using chloroform fumigation...
extraction method (Jenkinson et al. 2004). Soil pH (H₂O) was measured by using four composite samples consisting of four samples that were taken from near-by.

**Statistical analysis**

Since large portion of data did not follow the normal distribution (P < 0.05, Kolmogorov-Smirnov test) or homoscedasticity (P < 0.05, Levene’s test), Kruskal-Wallis test followed by Scheffe’s multiple comparison test was used. We assumed N₂O fluxes were higher than zero, thus replaced data lower than zero with zero. Spearman’s correlation coefficient was used to evaluate the relationship among variables. All statistical analyses were performed by Excel 2013 with statistical add-in software (SSRI).

**RESULTS**

As we hypothesized, N₂O emissions were higher in the CL forest (0.62 mg N m⁻² day⁻¹) than in the primary forest (0.17 mg N m⁻² day⁻¹), but had no differences between the primary and RIL forests (0.33 mg N m⁻² day⁻¹) (Fig. 1a). On the other hand, we did not observe any differences in CH₄ fluxes among the three forests (Fig. 1b). CH₄ fluxes showed negative values (−0.32 to −0.48 mg C m⁻² day⁻¹, Fig. 1b) as observed in most of the forest ecosystems (Potter et al. 1996). CO₂ emissions ranged from 2.6 to 4.0 g C m⁻² day⁻¹ (Fig. 1c). CO₂ emissions from the RIL forest were significantly higher than the other two forests (Fig. 1c).

Figs. 2 and 3 show soil physical and bio-chemical conditions in each forest, respectively. WFPS was higher in the CL forest (45 %) than the RIL forest (35 %) and the primary forest (30 %) (Fig. 2a). Soil temperature was higher in the two logged forests (25.9 °C and 25.7 °C in the CL and RIL forests, respectively) than the primary forest (25.2 °C) (Fig. 2b). No significant differences were observed in soil pH (H₂O) among the three forests (4.34, 4.17, and 4.29 in the primary, CL, and RIL forests, respectively) (Fig. 2c). MBC contents showed no significant differences among three forest types (Fig. 3a), but MBN contents were significantly higher in the CL forest than the primary forest (Fig. 3b). DOC contents in the primary forest were significantly lower than those in the two logged forests (Fig. 3c). The averaged value of DOC in the CL forest was two times larger than that of the primary forest (Fig. 3c). We did not observe any differences in DON contents among the three forest types (Fig. 3d). The RIL forest showed significantly higher NH₄⁺ contents than the primary forest (Fig. 3e). The CL forest showed much higher NO₃⁻ contents compared with the primary forest (>2 times higher) and the RIL forest (>3 times higher) (Fig. 3f).

By building a multiple regression model (step-wise method), we tried to explain the mechanisms controlling the impact of CL and RIL on the fluxes of non-CO₂ greenhouse gases. We focused only on N₂O emissions, because CH₄ fluxes did not show significant differences among the forests. Soil temperature, WFPS, MBC, MBN, DOC, DON, NH₄⁺, and NO₃⁻ were used as the indicators explaining the N₂O emissions, where only NO₃⁻ contents were chosen to do it (positive correlation). We also performed a single regression analysis, which showed that N₂O emissions were positively correlated with NO₃⁻ contents and soil temperature (Table 1).
DISCUSSION

The non-CO$_2$ greenhouse gas emissions observed in our study site were lower compared with other studies in tropical forests but in the range of previous data. N$_2$O emission rates observed in the present study (Fig. 1a) were at the lower end of the tropical forest average (0.23 to 3.5 mg N m$^{-2}$ day$^{-1}$, reviewed by Dalal and Allen 2008), but in the same range as other primary forests in tropical Asia (Ishizuka et al. 2002; Verchot et al. 2006). The CH$_4$ flux values (Fig. 1b) were slightly higher (i.e. CH$_4$ uptakes were lower) than the average of tropical rain forests...
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...emissions ranged from 2.6 to 4.0 g C m\textsuperscript{−2} day\textsuperscript{−1} or Dalal and Allen (2008) (−1.1 mg C m\textsuperscript{−2} day\textsuperscript{−1}). On the other hand, CO\textsubscript{2} emissions ranged from 2.6 to 4.0 g C m\textsuperscript{−2} day\textsuperscript{−1} (Fig. 1c), which are comparative with other tropical lowland forests (1.4–4.4 g m\textsuperscript{−2} day\textsuperscript{−1}) (Fernandes et al. 2002; Ishizuka et al. 2002; Kiese and Butterbach-Bahl 2002; Schwendemann et al. 2003; Dalal and Allen 2008; Yashiro et al. 2008).

As previously reported (Yashiro et al. 2008; Page et al. 2011), N\textsubscript{2}O emissions were enhanced by CL in our study site, while as we predicted RIL did not elevate the N\textsubscript{2}O emissions significantly (Fig. 1a). Since (i) both multiple and single regression model showed that NO\textsuperscript{−} contents and N\textsubscript{2}O emissions were positively correlated, and (ii) NO\textsuperscript{−} contents in the CL forest were significantly higher than those in the primary and RIL forests, we assumed that the quicker N cycling including nitrification and denitrification caused the higher N\textsubscript{2}O emissions in CL forest. As previously reported (Guntiñas et al. 2012), higher soil temperature and water content (WFPS) in the CL forest may have accelerated soil N cycling. Indeed, both WFPS and soil temperature were positively correlated with NO\textsuperscript{−} contents in our study (Table 1). Significantly lower microbial C/N ratio in the CL than primary forests (P < 0.01, Scheffe’s multiple comparison test; P < 0.01, Kruskal-Wallis test) may reflect the N-rich status of the CL forest. A greater remaining tree cover and a greater transpiration rate from the remaining trees in association with reduced harvest in the RIL forest (compared with the CL forest) probably mitigated the elevation of both WFPS and soil temperature, leading to a reduced N\textsubscript{2}O emissions compared with the CL forest.

Logging operation generally reduces CH\textsubscript{4} uptakes through soil compaction, increase in soil moisture, temperature, and accelerated N cycles (Steudler et al. 1991; Castro et al. 2000; Zerva and Mencuccini 2005). However, CH\textsubscript{4} fluxes showed no significant differences among the three types of forests (Fig. 1b), despite the higher WFPS and temperature and accelerated N cycles in CL forest (see discussion above). No correlations were observed among CH\textsubscript{4} fluxes and factors controlling CH\textsubscript{4} fluxes (Table 1).

The result is consistent with our previous report in the same region, where CH\textsubscript{4} fluxes in the CL forest did not differ from those in the primary forest (Mori et al. 2017).

It was unexpected that CO\textsubscript{2} emissions in the RIL forest was higher than those in the primary and CL forests. We could not fully explain this phenomenon, but one possible explanation would be that RIL provided optimum degree of disturbances and enhanced primary productions and root respirations through co-existence of late successional and pioneer species. Further observation is needed to clarify the mechanism.

Although the present study is not based on repeated gas flux measurements, we successfully demonstrated that (i) CL stimulated non-CO\textsubscript{2} greenhouse gas emissions (specifically N\textsubscript{2}O emissions) and (ii) RIL can mitigate the stimulation. In the future gas fluxes in the RIL forest need to be monitored more intensively and in a wider area including other regions.

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| Table 1. Spearman’s correlation coefficient among gas fluxes, soil chemical and microbial biomass contents. |
|---------------------------------------------------------------|
|                  NO\textsubscript{3}  | NH\textsubscript{4}  | DOC  | DON  | MBC  | MBN  | soil temperature | WFPS |
| N\textsubscript{2}O fluxes | 0.34 | NS   | NS   | NS   | NS   | NS   | 0.36 | NS   |
| CH\textsubscript{4} fluxes | NS | NS   | NS   | NS   | NS   | NS   | NS   | NS   |
| CO\textsubscript{2} fluxes | NS | 0.3  | NS   | NS   | NS   | NS   | NS   | NS   |
| NO\textsubscript{3} content | −  | NS   | NS   | NS   | NS   | NS   | 0.4  | 0.55 |
| NH\textsubscript{4} content | −  | 0.47 | NS   | NS   | NS   | NS   | 0.38 | NS   |
| DOC content | −  | 0.68 | NS   | 0.37 | 0.37 | 0.37 | 0.62 | 0.65 |
| DON content | −  | NS   | NS   | NS   | 0.29 | 0.29 | 0.38 | 0.38 |
| MBC content | −  | 0.71 | NS   | NS   | NS   | NS   | 0.29 | NS   |
| MBN content | −  | 0.41 | 0.58 | 0.58 | 0.58 | 0.58 | 0.58 | 0.58 |

WFPS, water-filled pore space. DOC, dissolved organic carbon. DON, dissolved organic nitrogen. MBC, microbial biomass carbon. MBN, microbial biomass nitrogen. NS, statistically not significant (p > 0.05).
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