Fluxes of $\text{CH}_4$ and $\text{N}_2\text{O}$ from soil under a tropical seasonal rain forest in Xishuangbanna, Southwest China

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Abstract

$\text{CH}_4$ and $\text{N}_2\text{O}$ fluxes from soil under a tropical seasonal rain forest in Xishuangbanna, Southwest China were measured for one year using closed static chamber technique and gas chromatography method. Three treatments were set in the studied field: (A) litter-free, (B) with litter, and (C) with litter and seedling. The results showed that the soil in our study was a sink of atmospheric $\text{CH}_4$ and source of atmospheric $\text{N}_2\text{O}$. The observed mean $\text{CH}_4$ fluxes from treatments A, B, and C were $-50.0 \pm 4.0$, $-35.9 \pm 2.8$, and $-31.6 \pm 2.8$ $\mu$gC/(m$^2$·h), respectively, and calculated annual fluxes in 2003 were $-4.1$, $-3.1$, and $-2.9$ kgC/hm$^2$, respectively. The observed mean $\text{N}_2\text{O}$ fluxes from treatments A, B, and C were $30.9 \pm 3.1$, $28.2 \pm 3.5$, and $50.2 \pm 3.7$ $\mu$gN/(m$^2$·h), respectively, and calculated annual fluxes in 2003 were $2.8$, $2.6$, and $3.7$ kgN/hm$^2$, respectively. Seasonal variations in $\text{CH}_4$ and $\text{N}_2\text{O}$ fluxes were significant among all the three treatments. The presence of litter decreased $\text{CH}_4$ uptake during wet season ($P < 0.05$), but not during dry season. There was a similar increase in seedlings-mediated $\text{N}_2\text{O}$ emissions during wet and dry seasons, indicating that seedlings increased $\text{N}_2\text{O}$ emission in both seasons. A strong positive relationship existed between $\text{CH}_4$ fluxes and soil moisture for all the three treatments, and weak relationship between $\text{CH}_4$ fluxes and soil temperature for treatment B and treatment C. The $\text{N}_2\text{O}$ fluxes correlated with soil temperature for all the three treatments.

Key words: global warming; greenhouse gases; rain forest; seasonal variability; soil moisture; soil temperature

Introduction

Since the 19th century, global surface temperature has been increasing, partly due to increasing concentration of greenhouse gases in the atmosphere. Methane ($\text{CH}_4$) is the most abundant greenhouse gas in the troposphere except water vapor and carbon dioxide, and its concentrations have doubled since the industrial revolution (IPCC, 2001). Methane consumption by dry soil is one of main ways to remove $\text{CH}_4$ from atmosphere which accounts for approximately 8% of the sink for atmospheric $\text{CH}_4$ (King, 1997). Tropical rain forest soils are recognized as an important sink for atmospheric $\text{CH}_4$ (Steudler et al., 1996), and humid tropical forests soils may account for 10%–20% of the sink methane (Potter et al., 1996a). Upland tropical forests in Costa Rica and forests in western and eastern Brazilian Amazonia have been considered as sinks for atmospheric $\text{CH}_4$ (Keller et al., 1993; Keller and Reiners, 1994; Verchot et al., 2000). It is known that main associated factors influencing the spatial and temporal variability of $\text{CH}_4$ fluxes include soil carbon, substrate quality, temperature, moisture, soil diffusivity, microbial activity, and N availability (Born et al., 1990; Castro et al., 1995; Dörr et al., 1993; Striegl, 1993; Verchot et al., 2000; Whalen and Reeburgh, 1996). Even so, there is large variability of $\text{CH}_4$ consumption by soils, and the mechanism involved is unclear so far.

Nitrous oxide ($\text{N}_2\text{O}$) is another important greenhouse gas. Although considerable uncertainty exists in the sources of atmospheric $\text{N}_2\text{O}$, there is growing evidence that $\text{N}_2\text{O}$ emission from soils is the largest contributor to the global atmospheric $\text{N}_2\text{O}$ budget mainly via microbial processes of nitrification and denitrification (Kroeze et al., 1999). Tropical forest soils play an important role in influencing $\text{N}_2\text{O}$ balance in the atmosphere (Matson and Vitousek, 1990; Riley and Vitousek, 1995), and are considered as the most important sources for soil borne $\text{N}_2\text{O}$ emissions (Goreau and De Mello, 1987; Potter et al., 1996b; Smith, 1997). According to a limited number of field measurements, the estimated $\text{N}_2\text{O}$ fluxes from the tropical rain forest soils varied within a broad range of 0.15–7.68 kgN/(hm$^2$·a) (Breuer et al., 2000; Kiese and Butterbach-Bahl, 2002; Livingston et al., 1988; Serca et
al., 1994; Verchot et al., 1999).

Marked diurnal or seasonal variations in the rate of CH$_4$ uptake and N$_2$O emission have been detected from soils of different forests (Keller et al., 1993; Luizao et al., 1989). Seasonal changes of both gas fluxes in tropical seasonal rain forest soils and the mechanisms involved are poorly understood (Kiese and Butterbach-Bahl, 2002; Kiese et al., 2003). Thus estimates of gas fluxes based on sporadic and short-term measurements do not fully reflect these dynamics (Matson and Vitousek, 1990; Verchot et al., 1999), which lead to the estimates of the sink strength for different tropical rain forest soils uncertainly (Breuer et al., 2000; Verchot et al., 2000). Understanding seasonal variation patterns of these fluxes are thus important for better estimations of these two gas fluxes associated with soil moisture and soil temperature. To improve the assessment of global CH$_4$ uptake and N$_2$O emission rates from tropical rain forests, more data are needed to collect. Of course, the presence of litters and seedlings may affect the seasonal variations of CH$_4$ and N$_2$O fluxes from tropical forest.

Tropical seasonal rain forest in Xishuangbanna is located on the northern edge of tropical Southeast Asia, where tropical forests from the south and subtropical forests from the north meet together. The processes of CH$_4$ and N$_2$O fluxes for such forest soils are largely unknown, except some short-term data (Werner et al., 2006). In order to improve the database for CH$_4$ and N$_2$O fluxes from this seasonal rain forest, we carried out this measurement. In view of the fact that local climate is predominated by tropical monsoon, which results in the alternation of dry season and wet (rainy) season, we tried to answer whether CH$_4$ and N$_2$O fluxes show also seasonal variations and to identify what are the key factors affecting the fluxes.

1 Materials and methods

1.1 Study sites

This study was carried out in a tropical seasonal rain forest in Xishuangbanna, Southwest China. Several decades meteorological data from Xishuangbanna Station for Tropical Rain Forest Ecosystem Studies in Chinese Ecosystem Research Network (CERN) show that mean annual temperature is 21.7°C. The mean annual precipitation is 1557 mm, and more than 87% of it occurs in wet season (April to October); the minimum monthly rainfall was 9.4 mm. The average annual relative air humidity is about 86%. The study site was in the 1 ha permanent plot located at 90°C. Precipitation data were recorded by the Xishuangbanna Station for Tropical Rain Forest Ecosystem Studies, Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences (CAS).

1.3 Measurements of CH$_4$ and N$_2$O fluxes

N$_2$O and CH$_4$ fluxes were measured using closed static chamber made of stainless steel, with an open-bottom cubic chamber (length × width × height, 50 cm × 50 cm × 50 cm, equipped with two small fans inside). The chamber was wrapped with a layer of sponge and aluminum foil in the plot were divided into three layers. Tree layer A (upper canopy) was over 30 m tall. The average tree height of the plot was 18.6 m, average basal area was 0.078 m$^2$/tree, and stand density was 386 trees/ha$^2$. The forest was dominated by Pometia tomentosa (Bl.) Teysm. et Binn., Barringtonia macrostachya (Jack) Kurz, Giromniera subaequalis Planch. and Terminalia myriocarpa Heurck et Muell.-Arg (Cao et al., 1996). Soil under the forest was oxisol developing from yellow sandstone. Litter layer was normally about 2–5 cm, and humus layer was about 1–3 cm. Organic matter content of 0–10 cm mineral soil layer was about 22 g/kg. The main characteristics of the soil were surveyed by Sha et al. (2000) (Table 1).

<table>
<thead>
<tr>
<th>Soil pH</th>
<th>Organic matter (g/kg)</th>
<th>Total N (g/kg)</th>
<th>C/N ratio</th>
<th>NH$_4^+$-N (mg/kg dry soil)</th>
<th>NO$_3^-$-N (mg/kg dry soil)</th>
<th>Bulk density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.75±0.09</td>
<td>21.7±0.14</td>
<td>1.40±0.02</td>
<td>11.33±0.87</td>
<td>19.75±4.93</td>
<td>4.71±1.37</td>
<td>1.08±0.04</td>
</tr>
</tbody>
</table>

Values are the means ±SE.
to minimize temperature changes during the period of sampling. Permanent stainless steel base flumes (length \( \times \) width \( \times \) height, 50 cm \( \times \) 50 cm \( \times \) 30 cm) with grooves (2 cm in width) were installed into the soil two weeks before the first gas sampling to eliminate disturbances. For the collection of gas samples, the chambers were placed over the base flumes, and the water was filled in the grooves to ensure gas tightness. Samples were taken with 100 ml plastic syringes attached a three-way stopcock at 0, 10, 20, 30 min following chamber closure, respectively. The first 100 ml gas was abandoned, because it might contain the gas taken at the latest sampling. Gas samples collected were normally analyzed within 24 h using gas chromatography.

The N\(_2\)O and CH\(_4\) concentrations were simultaneously analyzed with a modified gas chromatography (Agilent 4890D, USA) equipped with electron capture detector (ECD) and flame ionization detector (FID), respectively. Details of the measuring system and associated method have been described by Wang and Wang (2003). Gas fluxes are calculated from linear regressions of concentrations inside the chambers against the closure time according to the following equation:

\[
F = \frac{V \cdot P \cdot T_0}{A \cdot P_0 \cdot T} \frac{dC_i}{dr}
\]

where, \( F \) is CH\(_4\) and N\(_2\)O gas flux (mg/(m\(^2\)-h)), \( \rho \) is gas density at the test temperature (mg/m\(^3\)), \( V \) is chamber volume available (m\(^3\)), \( A \) is bottom area of the chamber (m\(^2\)), \( P \) is atmospheric pressure in the field (hPa), \( P_0 \) is atmospheric pressure under standard conditions (hPa), \( T_0 \) is absolute air temperature under standard conditions (25°C), \( T \) is absolute air temperature in chamber at the time of sampling (°C), \( C_i \) is concentration of mixed volume ratios of gases in chamber at time \( t \) (10\(^{-6}\)).

Positive values indicate an emission of a gas from the soil to the atmosphere, whereas negative values indicate gas consumption by the soil. In general, measurement sets that did not yield a linear regression with \( r > 0.90 \) were rejected, and in consequence led to the exclusion of approximately 17% of the data observed.

1.4 Statistical analyses

Normal probability was tested by the Kolomogorov-Smirnov test for CH\(_4\) and N\(_2\)O fluxes. Because of normal distribution of CH\(_4\) fluxes for all treatments, multiple range test (least squares distance, LSD) by one-way ANOVA was performed to identify differences among treatments and between both dry and wet seasons. N\(_2\)O fluxes for treatments B and C were non-normal distribution, so the non-parametric Mann-Whitney test was performed to identify differences of N\(_2\)O fluxes among treatments and between seasons. Correlation analyses were used to examine relationships between CH\(_4\) fluxes and N\(_2\)O fluxes, and the following parameters, such as soil surface temperature, soil moisture, soil temperature at 5 cm depth. Test of significance of differences between soil surface temperature and soil temperature at 5 cm depth was performed by using the independent-samples t-test. The software SPSS 12.0 (SPSS Inc., United States) was used for all statistical analyses.

2 Results

2.1 Rainfall, temperature, soil moisture and seedling biomass

The largest monthly precipitation occurred in August (389.9 mm), whereas the smallest monthly precipitation in November was 0.2 mm and in December 1.4 mm. The precipitation in January 2004 was 4.8 mm. A distinct wet season can be observed from May to early November with more than 78% of the year 2003 precipitation (Fig.1a), and the total precipitation (1244.4 mm) in 2003 was lower than that in normal years.

Air temperature, soil temperature at 0 and 5 cm depth were measured over the year. There were no significant differences in air temperature (18.78±0.19°C), soil temperature at 0 cm (19.32±0.16°C) and 5 cm depth (19.25±0.16°C). Linear regressions were analyzed between temperatures at 5 and 0 cm (\( T_{5\,cm} = 0.97T_{0\,cm} + 0.47 \), \( r^2 = 0.988 \)) and between temperatures at 5 cm and in air (\( T_{5\,cm} = 0.82T_{air} + 3.90 \), \( r^2 = 0.969 \)). Therefore, only the soil temperature at 5 cm depth is shown in Fig.1b.

Starting from May 2003, soil water content at 7 cm depth was measured. The changes of soil moisture paralleled with the variation of precipitation (Fig.1c). However soil moisture was still relatively high because of heavy fog at night and in the morning during November and December although the precipitation in this period was low.

The above-ground and under-ground parts of seedling biomass were small, with 33.7±14.3, 10.5±6.1 g/m\(^2\) in March, respectively, and 60.2±14.6, 19.6±11.3 g/m\(^2\) in December, respectively.

2.2 Mean fluxes of CH\(_4\) and N\(_2\)O fluxes over one year field measurements

The soils consumed atmospheric CH\(_4\), with except of the measures in August and September (strong precipitation months, Figs.1d and 1a). There were significant differences in annual mean of CH\(_4\) uptake between treatments A and B (\( P = 0.005 \)) and between treatments A and C (\( P = 0.000 \)). Treatments B and C had the similar CH\(_4\) fluxes (\( P = 0.390 \) (Table 2). This result revealed that litter was an important factor, reducing CH\(_4\) uptake of the soil by 29%. On the basis of our data set, mean annual CH\(_4\) fluxes were \(-50.5±4.0, -35.9±2.8, -31.6±3.7 \) µgC/(m\(^2\)-h) from treatments A, B, and C, respectively.

Soils showed N\(_2\)O emission over the year except in November and December (the smallest precipitation months in the year). Significant differences were not observed between treatments A and B (\( P = 0.584 \)) but existed between treatments A and C (\( P = 0.000 \)) and between treatments B and C (\( P = 0.000 \)). Seedlings strongly increased N\(_2\)O emission from the soil by 63%, but litter did not modulate the N\(_2\)O flux. Mean annual N\(_2\)O fluxes were 30.9±3.1, 18.2±3.5, 50.2±3.7 µgN/(m\(^2\)-h) from treatments
Fig. 1  Daily precipitation (a), soil temperature at 5 cm depth (b), soil moisture content (c), mean weekly CH$_4$ flux (d), and mean weekly N$_2$O flux (e).

Table 2  Annual means, minimum and maximum of CH$_4$ and N$_2$O fluxes

<table>
<thead>
<tr>
<th>Treatment</th>
<th>CH$_4$ flux ($\mu$gC/(m$^2$·h))</th>
<th>N$_2$O flux ($\mu$gN/(m$^2$·h))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Means</td>
<td>Min.</td>
</tr>
<tr>
<td>A</td>
<td>–50.0±4.0$^a$ (125)</td>
<td>–210.0</td>
</tr>
<tr>
<td>B</td>
<td>–35.9±2.8$^b$ (130)</td>
<td>–167.8</td>
</tr>
<tr>
<td>C</td>
<td>–31.6±3.7$^b$ (125)</td>
<td>–172.4</td>
</tr>
</tbody>
</table>

Different superscripts above means in a column indicate significant differences on the 95% confidence level. CV is coefficient of variation, the value in parenthesis is number of observation.

A, B and C, respectively, and their CV values were 114.9%, 140.1%, 82.6%, respectively.

2.3 Mean fluxes of CH$_4$ and N$_2$O fluxes during dry and wet seasons

Significant difference of CH$_4$ fluxes between both seasons could be demonstrated in all the three treatments. CH$_4$ uptakes in wet season from three treatments were lower by 49% to 187% than those in dry season. The highest mean CH$_4$ uptake rates (~58.4±4.4 µgC/(m$^2$·h)) were recorded in treatment A during dry season, and the lowest mean CH$_4$ uptake rates (~16.3±4.9 µgC/(m$^2$·h)) were from treatment C during wet season. Compared to treatments A and B, the CH$_4$ uptake for treatment C decreased both in wet and dry season. The CV values of CH$_4$ fluxes in dry season (62.9% to 83.8%) were lower than those in wet season (120.7% to 237.6%). This indicated a higher temporal variability in wet season than in dry season. The CH$_4$ fluxes between
treatments A and B had a significant difference only in wet season, whereas CH$_4$ fluxes between treatments A and C had significant differences in both seasons.

N$_2$O fluxes for all treatments during dry season significantly were reduced as compared to those during wet season ($P = 0.013$, $P = 0.022$, $P = 0.001$, respectively, Table 3). Of all the three treatments, the highest mean N$_2$O flux (60.3 ± 5.7 µgN/(m$^2$·h)) was found from treatment C during wet season, and the lowest mean N$_2$O flux (19.8±4.7 µgN/(m$^2$·h)) was from treatment B in dry season. The CV values of N$_2$O fluxes for treatments A (160.0%) and B (372.1%) in dry season were higher than those in wet season (71.5%, 85.7%, respectively), while CV values of N$_2$O fluxes for treatment C were close in dry and wet seasons (71.5%, 85.7%, respectively).

N$_2$O emissions for treatments A and B in both seasons were similar, but N$_2$O emissions for treatment C were significantly different from treatment A in dry and wet seasons ($P = 0.001$, $P = 0.017$), and also significantly different from treatment B in dry and wet seasons ($P = 0.000$, $P = 0.003$).

2.4 Correlation of CH$_4$, N$_2$O fluxes and soil temperature, moisture

Correlations between mean weekly CH$_4$, N$_2$O fluxes and soil temperature at 5 cm depth and soil moisture at 7 cm depth were tested. CH$_4$ fluxes correlated significantly with soil moisture in treatments A, B, and C ($P < 0.01$ for all treatments). Some correlation between CH$_4$ flux and soil temperature were found in treatments B and C ($P < 0.01$, $P < 0.01$, respectively), but no correlation exits in treatment A. Because mean weekly CH$_4$, N$_2$O fluxes were normal distribution, we simulated linear regression between weekly mean fluxes every treatment and mean temperature or moisture. Linear regression between CH$_4$ fluxes and soil moisture explained 37%, 60%, and 59% of the variability, for treatments A, B and C, respectively (Fig.2).

N$_2$O fluxes had strong positive correlation with soil temperature at 5 cm depth in three treatments ($P < 0.01$ for all treatments), but had no significant correlation with soil moisture. Linear regression between N$_2$O fluxes and soil temperature explained 27%, 28% and 21% of the variability, for treatments A, B and C, respectively (Fig.3).

3 Discussion

3.1 Annual CH$_4$ and N$_2$O fluxes

Because weekly measurement of trace gas fluxes could provide a reliable basis for estimating annual budgets of CH$_4$ and N$_2$O fluxes in tropical rain forest sites (Kiese et al., 2003), so we use the linear regression between CH$_4$ fluxes and soil moisture at 7 cm depth to estimate daily and annual fluxes. Calculated annual CH$_4$ fluxes for treatments A, B, and C in 2003 were –4.1, –3.1, and –2.9 kgC/(hm$^2$·a), respectively. The published reports showed tropical rain forests soils could function as sinks as well as sources for atmospheric CH$_4$ ranging from –19.7 to 36.1 kgC/(hm$^2$·a) (Delmas et al., 1992; Keller et al., 1990; Potter et al., 1996a; Steudler et al., 1991, 1996; Tathy et al., 1992). As compared with them, the calculated annual CH$_4$ fluxes for treatments A and B at our study site were well within the range given above. Our results were very close to the values in Brazilian Amazon tropical rain forests (from –3.4 to –5.9 kgC/(hm$^2$·a)) and in Costa Rica humid forests (–3.5 kgC/(hm$^2$·a)) (Keller and Reiners, 1994; Steudler et al., 1996). Some far lower values were found, such as
–1.4 kgC/(hm²·a) for primary forest soils in Paragominas, Brazil (Verchot et al., 2000), 1.6 kgC/(hm²·a) in Barro Colorado, Panama (Keller et al., 1990). CH₄ flux from soil to the atmosphere depends on the balance between two processes of methanogenesis and methanotrophy, which are influenced by some factors including soil carbon, substrate quality, temperature, moisture, microbial activity, pH, and N availability. A main controller of the magnitude of CH₄ uptake in some forests is the gas permeability of the soil for atmospheric CH₄ and O₂ involving soil moisture and soil texture (Crill, 1991; Kiese et al., 2003). The variability in CH₄ fluxes among these tropical forests may be due to differences in above factors.

Calculated annual N₂O fluxes for treatments A, B, and C in 2003 were 2.8, 2.7, and 3.7 kgN/(hm²·a), respectively. The value for treatments A and B were very close to that for tropical primary rain forests soils in Costa Rica (2.5 kgN/(hm²·a)), although their mean annual precipitation (4200 mm) was much higher than our study region (Matson and Vitousek, 1987). Compare with those tropical primary rain forests with similar annual precipitation, our calculated N₂O fluxes were lower than for Mayombo, Congo and for Kauri Creek, Australia (6.7, 5.4 kgN/(hm²·a)), respectively (Breuer et al., 2000; Serca et al., 1994), but higher than that for Manaus, Brazil and Queensland, Australia (1.0, 1.2, 1.0 kgN/(hm²·a), respectively (Breuer et al., 2000; Kiese et al., 2003; Livingston et al., 1988). Some studies support that N₂O flux rates are tightly related with N turnover rates in tropical forests (Matson and Vitousek, 1987). N turnover includes mineralization, nitrification and denitrification (the latter two are the key processes in N₂O production). As same as other forests, the primary regulating processes of N₂O emissions take place in the uppermost soil horizons in tropical forests (Breuer et al., 2000). Compared to the tropical rain forest in Australia, Brazil, Kongo, Puerto Rico, the total N of surface soils in our study site (0.14%) is relatively lower than those mentioned above forests (from 0.15% to 0.80%, Breuer et al., 2000; Livingston et al., 1988; Matson et al., 1990; Serca et al., 1994; Sha et al., 2000; Verchot et al., 1999). The nitrification rate (16.3 mg NO₃⁻/N/(kg·30 d)) is close to tropical rain forest in Venezuelan Amazon (14.9 mg NO₃⁻/N/(kg·30 d)), but net N mineralization (6.6 mg (NH₄⁺+NO₃⁻)/N/(kg·30 d)) is lower than the former (14.0 mg (NH₄⁺+NO₃⁻)/N/(kg·30 d), (Montagnini and Buschbacher, 1989; Sha et al., 2000). The difference in net mineralization and total N of soils could responsible for the fact that N₂O flux from our study site differs from other tropical forests.

### Table 3 Means of CH₄ and N₂O fluxes from three treatments in two seasons

<table>
<thead>
<tr>
<th>Season</th>
<th>Treatment A</th>
<th>Treatment B</th>
<th>Treatment C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average CH₄ flux (µgC/(m²·h))</td>
<td>Average N₂O flux (µgN/(m²·h))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry</td>
<td>–58.4±4.4³b (70)</td>
<td>–50.1±4.0³b (67)</td>
<td>–46.7±4.9³b (63)</td>
</tr>
<tr>
<td>Wet</td>
<td>–39.3±6.8³a (55)</td>
<td>–20.8±3.2³b (63)</td>
<td>–16.3±4.9³b (62)</td>
</tr>
</tbody>
</table>

Different superscripts indicate significant differences (*P < 0.05) in fluxes, a and b are between the two seasons in a given treatment; A and B are between treatments in given season. The number of observation is in the parenthesis below the mean. Negative values indicate uptake, and positive values indicate emission.

#### 3.2 Roles of litters and seedlings in the CH₄ and N₂O fluxes

Litter reduced CH₄ uptake of the soil by 29% at our site, which was in agreement with in a boreal Scots pine forest (Saari et al., 1998). The consumption of CH₄ is from methanotrophs in aerobic soils that occurs in the surface soils and oxidize much of the CH₄ before it diffuses to the atmosphere. CH₄ is the end product of anaerobic decomposition of organic matter by methanogens in anaerobic soils (Dong et al., 1998; Schütz et al., 1991). In wet season, fast decomposition of litter in optimum soil moisture and temperature consumed much oxygen, which caused oxygen deficiency in the soil. On the other hand, the soil of the study site had high soil N mineralization in wet season (Sha et al., 2000), which further decreased soil aeration (Maljanen et al., 2001). Under these conditions, soils consumed less CH₄ in wet season than in dry season. For the soil with litter, CH₄ diffusion from ambient atmosphere to the soil was limited by relatively tighter coverage of litter in wet season than in dry season, which also decreased soil aeration in wet season. On the contrary, litter decomposed slowly because of relatively lower moisture and temperature of air and soil in dry season. This limited the activity of methanogens. So litter has little effect on CH₄ flux in dry season. This could be the mechanism for that litter decreased CH₄ uptake significantly during wet season. Further studies, of course, are still needed.

Previous studies had shown that decomposition of fine roots could stimulate N mineralization and nitrification, leading to greater potential for losses of N₂O from soils (Chen et al., 2002; Silver and Vogt, 1993). Silver et al. (2005) found that root mortality and decomposition were important mechanisms contributing to increased N₂O emissions in two-year study. The short-term root mortality in tropical forest soils also increased soil N₂O emissions (Keller et al., 2000; Matson and Vitousek, 1990; Varner et al., 2003). On the other hand, some upland woody plants, especially their seedlings, can serve as a conduit for dissolved N₂O from the root zone to the atmosphere from leaves and shoots by transpiration (Chang et al., 1998; Pihlatie et al., 2005; Rusch and Rennenberg, 1998), and some plants can convert nitrate to N₂O in leaves, but which contribute relatively small fraction of the total N₂O emission from plants (Hakata et al., 2003). Our study showed that seedlings increased N₂O emission of the soil by 63%. We postulated that seedlings probably contributed to high net N₂O emission mainly through the supply of under-ground litter or root exudates. Due to absence of related factors measurement, the mechanism of an increase
N$_2$O emission resulting from seedling regulation should be further studied.

3.3 Effect of soil temperature and moisture on CH$_4$ and N$_2$O fluxes

It was well known that consumption of CH$_4$ by methanotrophic bacteria in aerated soil causes the uptake of atmospheric CH$_4$ (King, 1997; Mancinelli, 1995; Striegl, 1993). Aeration of soils was adjusted by soil moisture. As soil moisture increased, air-filled porosity decreased, resulting in restricted CH$_4$ diffusion into the soil and lower rates of consumption (Born et al., 1990; Dörr et al., 1993; Keller et al., 1993; Striegl, 1993). Verchot et al. (2000) observed that formation of anaerobic soil microsites may cause a switch from a consistent soil CH$_4$ sink to an intermittent CH$_4$ source. Our results demonstrated this seasonal variation, which were consistent with the published findings (Kiese et al., 2003). The strong correlation between CH$_4$ uptake and soil moisture was observed in many forest soils (Born et al., 1990; Castro et al., 1995; Striegl, 1993; Verchot et al., 2000; Whalen and Reeburgh, 1996). Generally, CH$_4$ oxidation in the soil correlated positively with soil temperature (Crill, 1991; King, 1997; Mancinelli, 1995), but CH$_4$ uptake had only a weak temperature dependency (Born et al., 1990; Dörr et al., 1993; Koschorreck and Conrad, 1993). The optimal temperatures for CH$_4$ oxidation were thought in the range from 20 to 30°C (Nesbit and Breitenbeck, 1992). Due to the soil temperatures in wet season in our study site varied in a small range from 20 to 25°C, CH$_4$ uptake of the soil was also weakly sensitive to soil temperature in wet season. For treatment A in wet season, the soil water could be evaporated quickly without litter coverage after continuous fine days, which enhanced aeration of the soil. Along with the favorable soil temperature, CH$_4$ uptake of treatment A showed high in the June and July. When it rained continuously, the soil moisture increased, which resulted in quick decrease of CH$_4$ oxidation and increase of CH$_4$ production. The larger CV of CH$_4$ fluxes for treatment A in wet season than in dry season was possibly caused by the large fluctuation of soil moisture in wet season. In dry season, high gas diffusion in the soil due to low soil moisture was favorable for CH$_4$ oxidation and unfavorable for litter decomposition, so all treatments had high CH$_4$ uptake.

N$_2$O fluxes had positive correlation with soil temperature in three treatments, which was in well agreement with the results from other forests (Steudler et al., 1991; Papen and Butterbach-Bahl, 1999). Temperature regulated N$_2$O emission of soils through its influence on microbial activity, such as nitrifiers and denitrifiers. The relatively high temperature in wet season was benefit for microbial activity, which partly explained that N$_2$O fluxes for all treatments varied seasonally high emissions in wet season and with low emissions in dry season. This seasonal variation of N$_2$O fluxes was also observed by others (Breuer et al., 2000; Garcia et al., 1991; Kiese and Butterbach-Bahl, 2002; Steudler et al., 1991; Verchot et al., 1999). The contribution of nitrification and denitrification to the N$_2$O emission was observed almost identical in some ecosystems, but the growing evidence showed that nitrification was the key process for N$_2$O production in forest ecosystem (Papen and Butterbach-Bahl, 1999). In our study site, soil NH$_4^+$-N concentration was high in April and July and much lower in June. And soil NO$_3^-$-N concentration was the highest in July (Meng et al., 2001). High soil NH$_4^+$-N and NO$_3^-$-N concentration supplied lots of substrate for nitrifiers and denitrifiers. Large N$_2$O emissions in June and July were due to nitrification, and denitrification taking place simultaneously at high rates under favorable temperature and abundant substrate supply. The possible plant transportation of N$_2$O through transpiration could further enhanced soil N$_2$O emissions (Chang et al., 1998; Pihtlatie et al., 2005; Rusch and Rennenberg, 1998). When NH$_4^+$ and NO$_3^-$ consumed quickly at the end of June, nitrification and denitrification were limited. This explained why the soil in our study site had strong N$_2$O emission and fluctuated fiercely. Compared with CV for N$_2$O emission from tropical rain forest soils in eastern Amazonia (100%–118%), and in Australia (14%–132%) (Breuer et al., 2000; Verchot et al., 1999), the CVs of three treatments in our study site were close to them. But there was lower CV value of 37%–61% from the wet tropical forest of Queensland (Kiese and Butterbach-Bahl, 2002).

Previous reports indicated that soil moisture was one of the most important factors influencing N$_2$O emissions from tropical forest soils, such as a log linear relationship between N$_2$O emissions and WFPS (soil water filled pore space) for an old growth forest and a secondary forest in Costa Rica (Kiese and Butterbach-Bahl, 2002; Keller et al., 1994). The tropical forests in Costa Rica had relatively N rich soils. Soils from tropical agriculture ecosystem to pasture with low nitrogen (0.4%–0.5%) had a weak or none dependency of N$_2$O fluxes from increasing soil moisture (Dobbie et al., 1999; Weitz et al., 2001). Our study showed that N$_2$O emission was insensitive to soil moisture, possibly resulting from lower soil nitrogen content (0.14%, Sha et al., 2000). Significant differences in N$_2$O emission between different years existed in tropical rain forests soils in Australia (Kiese et al., 2003). We do not know how inter-annual N$_2$O fluxes in our study vary. As pointed out previously, the rainfall in 2003 was lower than the long-term mean precipitation and other factors may inter-annually vary, which resulted in gas dynamics. In order to improve estimation both CH$_4$ and N$_2$O fluxes from rain forest soils, inter-annual variability cannot be neglected and long-term field measurements should be conducted.

4 Conclusions

In this study, we estimated annual soil CH$_4$ and N$_2$O fluxes through simple linear regressions between gases and soil moisture and temperature. The results showed that both gases fluxes seasonally varied. Litter significantly reduced soil CH$_4$ uptake and seedling significantly increased soil N$_2$O emission. The study confirmed soil moisture was an important factor influencing soil CH$_4$ flux, and there...
was a weak relationship between soil temperature and soil CH$_4$ flux. Soil temperature was identified as a key factor regulating N$_2$O emission.

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