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Fluxes of CH_4 and N_2O from soil under a tropical seasonal rain forest in Xishuangbanna, Southwest China

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Abstract

CH_4 and N_2O 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 CH_4 and source of atmospheric N_2O. The observed mean CH_4 fluxes from treatments A, B, and C were –50.0 ± 4.0, –35.9 ± 2.8, –31.6 ± 2.8 μgC/(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 N_2O fluxes from treatments A, B, and C were 30.9 ± 3.1, 28.2 ± 3.5, 50.2±3.7 μgN/(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 CH_4 and N_2O fluxes were significant among all the three treatments. The presence of litter decreased CH_4 uptake during wet season ($P < 0.05$), but not during dry season. There was a similar increase in seedlings-mediated N_2O emissions during wet and dry seasons, indicating that seedlings increased N_2O emission in both seasons. A strong positive relationship existed between CH_4 fluxes and soil moisture for all the three treatments, and weak relationship between CH_4 fluxes and soil temperature for treatment B and treatment C. The N_2O 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 (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 CH_4 from atmosphere which accounts for approximately 8% of the sink for atmospheric CH_4 (King, 1997). Tropical rain forest soils are recognized as an important sink for atmospheric CH_4 (Steudler *et al*., 1996), and humid tropical forests soils may account for 10%–20% of the soil 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 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 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 CH_4 consumption by soils, and the mechanism involved is unclear so far.

Nitrous oxide (N_2O) is another important greenhouse gas. Although considerable uncertainty exists in the sources of atmospheric N_2O, there is growing evidence that N_2O emission from soils is the largest contributor to the global atmospheric N_2O budget mainly via microbial processes of nitrification and denitrification (Kroeze *et al*., 1999). Tropical forest soils play an important role in influencing N_2O balance in the atmosphere (Matson and Vitousek, 1990; Riley and Vitousek, 1995), and are considered as the most important sources for soil borne N_2O emissions (Goreau and De Mello, 1987; Potter *et al*., 1996b; Smith, 1997). According to a limited number of field measurements, the estimated N_2O 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*

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al., 1994; Verchot *et al*., 1999).

Marked diurnal or seasonal variations in the rate of CH_4 uptake and N_2O 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_2O 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_2O 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_2O fluxes for such forest soil are largely unknown, except some short-term data (Werner *et al*., 2006). In order to improve the database for CH_4 and N_2O 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_2O 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 hm^2 permanent plot located on a small flat (21°56′N, 101°16′E, alt. 720 m) between two hills. This vale was a typical site for the distribution of local seasonal rain forest. Previous tree species census indicated that there were 120 tree species with dbh (diameter at breast height) ⩾ 10 cm in this plot. The trees 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/hm^2. The forest was dominated by *Pometia tomentosa* (Bl.) Teysm. et Binn., *Barringtonia macrostachya* (Jack) Kurz, *Gironniera 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).

1.2 Experiments

Gas samples were taken once each week between local time (Beijing Time) 09:00 and 11:30 from January 27, 2003 to January 18, 2004. To determine the effect of litter and seedling on CH_4 and N_2O fluxes, three treatments were set in the field: (A) litter-free (litter and seedling were removed in advance), (B) with litter (litter was intact with thickness of 2–5 cm), and (C) with litter and seedling. The treatments were applied thrice.

Air temperature inside and outside the chambers, soil surface temperature and soil temperature at 5 cm depth were measured with four portable temperature probes (JM624 digital thermometer, Living-Jinming Ltd., China). Soil moisture (*V*/*V*) was measured using Moisture probe meter (MPM160, Meridian Measurement, China) when gas was sampled. To eliminate errors, measures of soil water contents were done at different direction outside the chambers. The mean of five measures was calculated as soil moisture in the chamber.

Seedling biomass was measured as dry matter every three months. We used the same species and same size around the plots to estimate the seedling biomass. The seedling was dug out and cleaned with water and clipped at the seedling base for separating under-ground biomass from the whole seedlings. Finally, both above-ground and under-ground parts were dried in oven to constant weight 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_2O fluxes

N_2O 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

Table 1 Main characteristics of the 0–10 cm surface mineral soils from measuring site

Soil pH	Organic matter (g/kg)	Total N (g/kg)	C/N ratio	NH_4^+-N (mg/kg dry soil)	NO_3^--N (mg/kg dry soil)	Bulk density (g/cm^3)
3.75±0.09	21.7±0.14	1.40±0.02	11.33±0.87	19.75±4.93	4.71±1.37	1.08±0.04

Values are the means ±SE.

to minimize temperature changes during the period of sampling. Permanent stainless steel base flumes (length × width × height, 50 cm × 50 cm × 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_2O 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:

$$F = \rho \frac{V}{A} \frac{P}{P_0} \frac{T_0}{T} \frac{\mathrm{d}C_t}{\mathrm{d}t} \quad (1)$$

where, F is CH_4 and N_2O gas flux (mg/(m^2·h)), ρ 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_t 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_2O 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_2O fluxes for treatments B and C were non-normal distribution, so the non-parametric Mann-Whitney test was performed to identify differences of N_2O fluxes among treatments and between seasons. Correlation analyses were used to examine relationships between CH_4 fluxes and N_2O 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_2O 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_2O 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_2O emission from the soil by 63%, but litter did not modulate the N_2O flux. Mean annual N_2O fluxes were 30.9±3.1, 18.2±3.5, 50.2±3.7 μgN/(m^2·h) from treatments

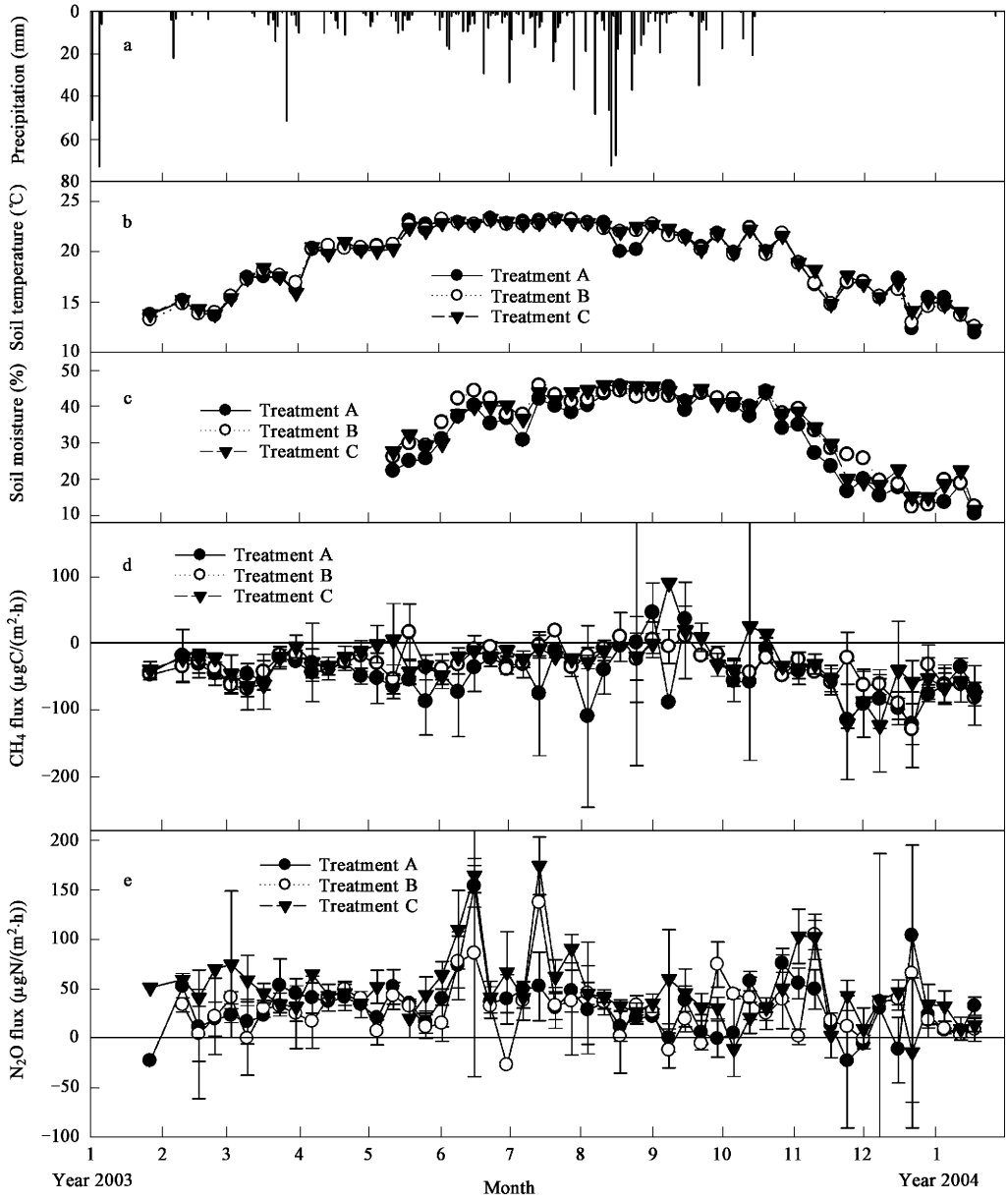

Fig. 1 Daily precipitation (a), soil temperature at 5 cm depth (b), soil moisture content (c), mean weekly CH_4 flux (d), and mean weekly N_2O flux (e).

Table 2 Annual means, minimum and maximum of CH_4 and N_2O fluxes

Treatment	CH_4 flux (μgC/(m^2·h))				N_2O flux (μgN/(m^2·h))			
	Means	Min.	Max.	CV (%)	Means	Min.	Max.	CV (%)
A	–50.0±4.0^a (125)	–210.0	130.7	88.8	30.9±3.1^b (128)	–100.7	168.2	114.9
B	–35.9±2.8^b (130)	–167.8	51.7	90.5	28.2±3.5^b (129)	–151.3	190.6	140.1
C	–31.6±3.7^b (125)	–172.4	166.9	133.3	50.2±3.7^a (127)	–68.1	264.8	82.6

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_2O 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_2O 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_2O flux (60.3 ± 5.7 μgN/(m^2·h)) was found from treatment C during wet season, and the lowest mean N_2O flux (19.8±4.7 μgN/(m^2·h)) was from treatment B in dry season. The CV values of N_2O fluxes for treatments A (160.0%) and B (372.1%) in dry season were higher than those in wet season (89.3%, 114.4%, respectively), while CV values of N_2O fluxes for treatment C were close in dry and wet seasons (71.5%, 85.7%, respectively). N_2O emissions for treatments A and B in both seasons were similar, but N_2O 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_2O fluxes and soil temperature, moisture

Correlations between mean weekly CH_4, N_2O 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_2O 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_2O 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_2O 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_2O fluxes

Because weekly measurement of trace gas fluxes could provide a reliable basis for estimating annual budgets of CH_4 and N_2O 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), 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

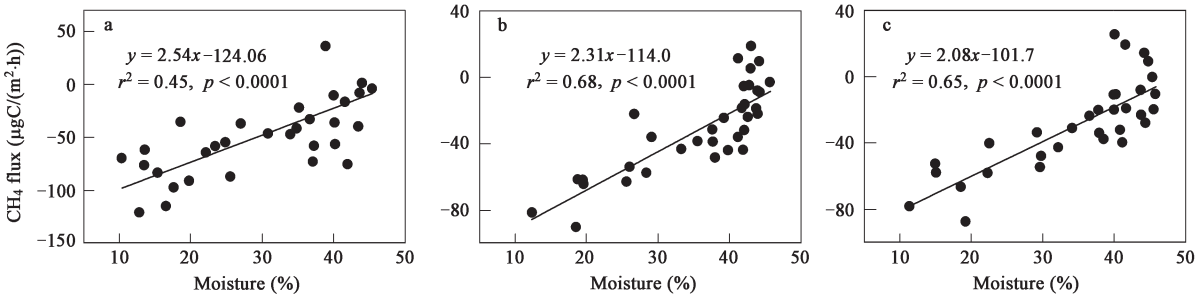

Fig. 2 Correlation between CH_4 and soil moisture at 7 cm depth. (a) treatment A; (b) treatment B; (C) treatment C.

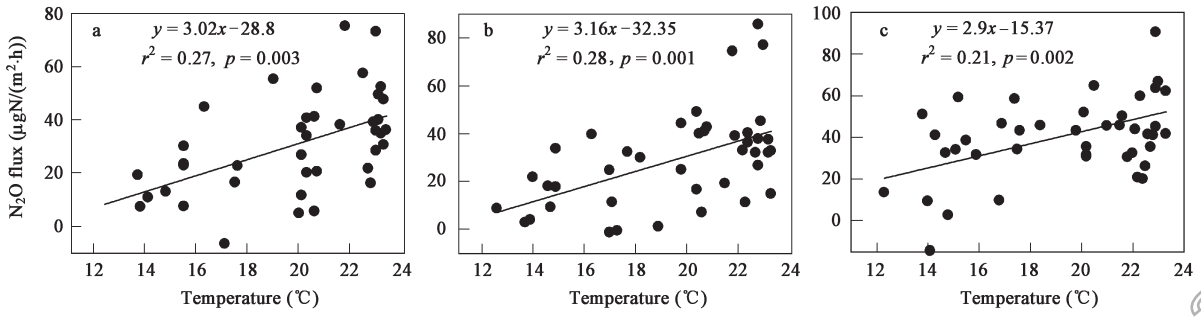

Fig. 3 Correlation between N_2O and soil temperature at 5 cm depth. a, b, c are the same as in Fig.2.

Table 3 Means of CH_4 and N_2O fluxes from three treatments in two seasons

Season	Average CH_4 flux (μgC/(m^2·h))			Average N_2O flux (μgN/(m^2·h))		
	Treatment A	Treatment B	Treatment C	Treatment A	Treatment B	Treatment C
Dry	-58.4 ± 4.4^{aA} (70)	-50.1 ± 4.0^{aA} (67)	-46.7 ± 4.9^{aA} (63)	22.3 ± 4.7^{bB} (58)	19.8 ± 4.7^{bB} (61)	37.7 ± 3.6^{bA} (57)
Wet	-39.3 ± 6.8^{bA} (55)	-20.8 ± 3.2^{bB} (63)	-16.3 ± 4.9^{bB} (62)	37.9 ± 4.1^{aB} (70)	35.7 ± 5.0^{aB} (68)	60.3 ± 5.7^{aA} (70)

Different superscripts indicate significant differences ($P \leqslant 0.05$) 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.

−1.4 kgC/(hm^2·a) for primary forest soils in Paragominas, Brazil (Verchot *et al*., 2000), 1.6 kgC/(hm^2·a) in Barro Colorado, Panama (Keller *et al*., 1990). CH_4 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 CH_4 uptake in some forests is the gas permeability of the soil for atmospheric CH_4 and O_2 involving soil moisture and soil texture (Crill, 1991; Kiese *et al*., 2003). The variability in CH_4 fluxes among these tropical forests may be due to differences in above factors.

Calculated annual N_2O fluxes for treatments A, B, and C in 2003 were 2.8, 2.7, and 3.7 kgN/(hm^2·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/(hm^2·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 N_2O fluxes were lower than for Mayombo, Kongo and for Kauri Creek, Australia (6.7, 5.4 kgN/(hm^2·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/(hm^2·a), respectively (Breuer *et al*., 2000; Kiese *et al*., 2003; Livingston *et al*., 1988). Some studies support that N_2O 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 N_2O production). As same as other forests, the primary regulating processes of N_2O 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 NO_3^--N/(kg·30 d)) is close to tropical rain forest in Venezuelan Amazon (14.9 mg NO_3^--N/(kg·30 d)), but net N mineralization (6.6 mg (NH_4^++NO_3^--N)/(kg·30 d)) is lower than the former (14.0 mg (NH_4^++NO_3^--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 N_2O flux from our study site differs from other tropical forests.

3.2 Roles of litters and seedlings in the CH_4 and N_2O fluxes

Litter reduced CH_4 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 CH_4 is from methanotrophs in aerobic soils that occurs in the surface soils and oxidize much of the CH_4 before it diffuses to the atmosphere. CH_4 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 CH_4 in wet season than in dry season. For the soil with litter, CH_4 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 CH_4 flux in dry season. This could be the mechanism for that litter decreased CH_4 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 N_2O 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 N_2O emissions in two-year study. The short-term root mortality in tropical forest soils also increased soil N_2O 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 N_2O 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 N_2O in leaves, but which contribute relatively small fraction of the total N_2O emission from plants (Hakata *et al*., 2003). Our study showed that seedlings increased N_2O emission of the soil by 63%. We postulated that seedlings probably contributed to high net N_2O 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_2O emission resulting from seedling regulation should be further studied.

3.3 Effect of soil temperature and moisture on CH_4 and N_2O 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_2O 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_2O 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_2O fluxes for all treatments varied seasonally high emissions in wet season and with low emissions in dry season. This seasonal variation of N_2O 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_2O emission was observed almost identical in some ecosystems, but the growing evidence showed that nitrification was the key process for N_2O 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_2O 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_2O through transpiration could further enhanced soil N_2O emissions (Chang *et al*., 1998; Pihlatie *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_2O emission and fluctuated fiercely. Compared with CV for N_2O 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_2O emissions from tropical forest soils, such as a log linear relationship between N_2O 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%–0.53%) had a weak or none dependency of N_2O fluxes from increasing soil moisture (Dobbie *et al*., 1999; Weitz *et al*., 2001). Our study showed that N_2O emission was insensitive to soil moisture, possibly resulting from lower soil nitrogen content (0.14%, Sha *et al*., 2000). Significant differences in N_2O emission between different years existed in tropical rain forests soils in Australia (Kiese *et al*., 2003). We do not know how inter-annual N_2O 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_2O 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_2O 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_2O 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_2O emission.

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