



The variation of greenhouse gas emissions from soils of various land-use/cover types in Jambi province, Indonesia

Shigehiro Ishizuka^{1,*}, Anas Iswandi², Yasuhiro Nakajima³, Seiichirou Yonemura³, Shigeto Sudo³, Haruo Tsuruta³ and Daniel Murdiyarso⁴

¹Forestry and Forest Products Research Institute, Sapporo, Hokkaido 062-8516, Japan; ²Department of Soil Science, Bogor Agricultural University (IPB), Jl. Raya Pajajaran Bogor 16143, Indonesia; ³National Institute for Agro-Environmental Sciences, Tsukuba, Ibaraki 305-8604, Japan; ⁴Department of Geophysics and Meteorology, Bogor Agricultural University (IPB), Jl. Raya Pajajaran Bogor 16143, Indonesia; *Author for correspondence (Tel: +81-11-851-4131; Fax: +81-11-851-4167; e-mail: ishiz03@ffpri.affrc.go.jp)

Key words: Flux measurement, Greenhouse gas, Land-use change, Nitrification, Sumatra of Indonesia, Tropical rain forest

Abstract

We measured fluxes of three greenhouse gases (N₂O, CO₂ and CH₄) from soils of six different land-use types at 27 temporary field sites in Jambi Province, Sumatra, Indonesia. Study sites included natural and logged-over forests; rubber plantation; oil palm plantation; cinnamon plantation; and grassland field. The ranges of N₂O, CO₂ and CH₄ fluxes were 0.13–55.8 μg N m⁻² h⁻¹; 1.38–5.16 g C m⁻² d⁻¹; –1.27–1.18 mg C m⁻² d⁻¹, respectively. The averages of N₂O, CO₂ and CH₄ fluxes at 27 sites were 9.4 μg N m⁻² h⁻¹, 3.65 g C m⁻² d⁻¹, –0.45 mg C m⁻² d⁻¹, respectively. The values of CO₂ and CH₄ fluxes were comparable with those in the reports regarding other humid tropical forests, while the N₂O flux was relatively lower than those of previous reports. The N₂O fluxes in each soil type were correlated with the nitrification rates of soils of 0–5 cm depth. In Andisols, the ratio of the N₂O emission rate to the nitrification rate was possibly smaller than that of the other soil types. There was no clear relationship between N₂O flux and the soil water condition, such as water-filled pore space. Seventeen percent of CH₄ fluxes were positive; according to these positive fluxes, we did not find a good correlation between CH₄ uptake rate and soil properties. Although we performed a chronosequence analysis to produce some hypotheses about the effect of land-use change by a limited amount of sampling at one point in time, further tests are required for the future.

Introduction

Greenhouse gas emissions from humid tropical ecosystems are clearly significant, but because of the limited quantity of data, the global estimate of greenhouse gas fluxes remains uncertain. To overcome this limitation, we need more spatial data, especially from the areas where there are few observations, such as Southeast Asia.

Land-use changes have the potential to affect the global budget of greenhouse gases (IPCC 1995). Over the last three decades in Indonesia, deforestation and land-use/cover changes have coincided with the development of the road infrastructure. During 1990 to

1997, the percentage deforestation rate of humid tropical forest in Southeast Asia (0.91%) was the largest in the world and annual loss of forest area was estimated as 2.5 G ha y⁻¹, which was almost the same as that of Latin America (Achard et al. 2002). But few data have been collected about the effect of land-use change on the greenhouse gas emissions in Southeast Asia.

The N₂O emission rate from natural ecosystems was calculated as 4.6–15.9 Tg N y⁻¹, equal to the amount from human activities (Prather et al. 2001). The N₂O emissions from humid tropical forests, estimated as 2.2–3.7 Tg N y⁻¹, were considered a key source. Bouwman et al. (1993) used a model with five parameters to determine the global N₂O emission rate

from natural soils; they estimated the annual global emission as 6.8 Tg N, 80% of which was released from tropical areas. According to their estimation, one reason for this high proportion of output from the tropics is that Ferralsols, which have a relatively high N₂O emission rate, comprise an area of 1116 Mha, one of the world's largest. Clearly, precise knowledge of the variation of N₂O flux in tropical regions is needed.

The global CH₄ rate of uptake by soils has been estimated at 15–35 Tg y⁻¹ (Potter et al. 1996). Humid tropical forest accounts for 10–20% of the global CH₄ uptake rate (Potter et al. 1996). The most important factor controlling the CH₄ uptake rate is the gas diffusion coefficient, which is determined by soil texture class (Born et al. 1990; Verchot et al. 2000). Land-use change from forest to active pasture caused a decrease in the CH₄ uptake rate (Keller et al. 1993; Keller and Reiners 1994), although degraded pasture consumed more CH₄ than primary forest (Verchot et al. 2000). Because of the limited number of studies, however, the effect of land-use change on the CH₄ uptake rate in tropical forests remains poorly quantified.

The annual global CO₂ flux from soils into the atmosphere is estimated to be 76.5 Pg C y⁻¹ (Raich and Potter 1995). The CO₂ flux from tropical moist forest was the highest of all terrestrial ecosystems (Raich and Potter 1995). Much like in the case of the CH₄ uptake rate, the effect of land-use change on CO₂ flux is obscure; some reports indicate an increase, while others indicate a decrease or no change in CO₂ emission rate (Raich and Schlesinger 1992).

An intensive field study on greenhouse gas emissions from soils of humid tropical forests in Sumatra, Indonesia, first reported by Ishizuka et al. (2002), revealed relatively lower N₂O flux and CO₂ fluxes than in previous reports involving multiple land-use types. These researchers obtained results showing that slash-and-burn had the adverse impact of accelerating N₂O emission rates and reducing CH₄ uptake rates. Because the field study focused on the seasonal variation of gas fluxes and on the impact of land-use change after deforestation, the area of land under study was relatively small, 3.7 km in latitude by 7.5 km in longitude (Ishizuka et al. 2002). It remains to be determined whether data is available or not for a larger area, and can therefore be applied to the entire area of Jambi, Sumatra, which has a wide variety of soil types and land-use types.

Our objective was to make an initial approach to represent the flux intensity and the relationship between land-use type and greenhouse gas emis-

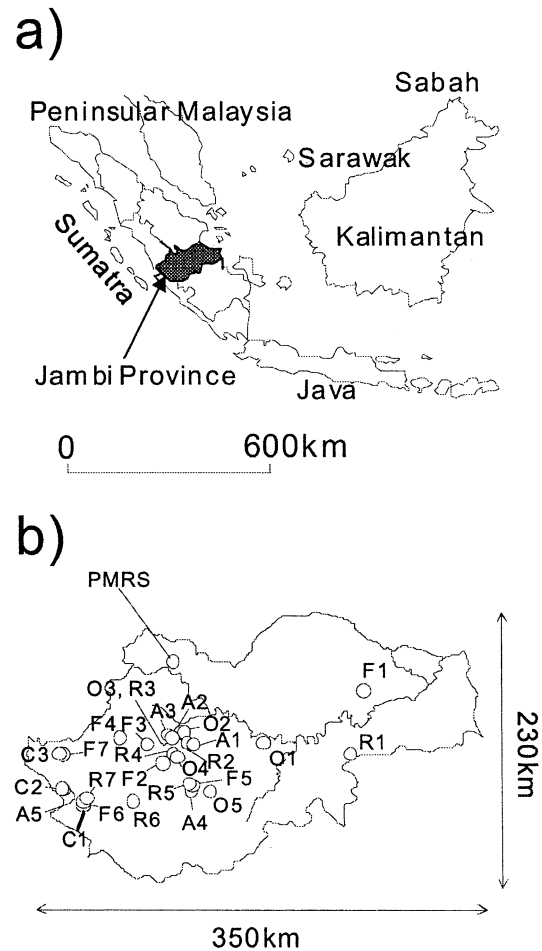


Figure 1. (a) The location of Jambi Province, and (b) the location of the 27 sites and PMRS.

sions in several hundred square kilometers in Jambi, Sumatra, Indonesia by (1) clarifying the major factor controlling greenhouse gas emissions related to the soil properties, and (2) performing a chronosequence analysis to evaluate the effect of land-use change.

Material and methods

Site description

Between September 4 and September 20, 2001, we performed an intensive field experiment, in a 245 km by 125 km area located in Jambi Province, central Sumatra, Indonesia (Figure 1). The region lies between the city Jambi in the east and the city Sungaipenuh in the west. The western part of Jambi contains a high mountainous area, whose altitude exceeds 1000 m. Going eastward, the altitude decreases;

the easternmost part, a swampy area, sits near sea level. The entire region (except the mountainous area) belongs to humid tropics. The annual rainfall ranged from 2112 to 2798 mm y^{-1} between January 1998 and December 2001 in the northwestern part of Jambi Province, called Pasir Mayang Research Site (PMRS; Ishizuka et al. 2002). It has yearly dry and wet seasons, which last from May to September and from October to April, respectively; the average monthly rainfall in the dry season (114 mm) was 42% of that in the rainy season (270 mm). According to four years of measurement in PMRS, the N_2O flux in September was 80% of the annual mean of N_2O flux and the differences in CO_2 and CH_4 fluxes between September and annual mean was less than that of N_2O (Tsuruta et al., unpublished data). The area's annual mean temperature is around 25 °C. The soil type around the mountainous area features Andisols, containing thick volcanic ash. In the middle part of Jambi Province, the main soil type is Ultisols, which has a low pH and a low nutrient level. The soil in the eastern part of Jambi Province has a wetter regime than that in the western part, whose soil is classified as Udults in USDA soil taxonomy.

In this experiment, we collected gas samples and soil samples at various land-use/cover types. Three land-use types are distributed widely throughout the province; rubber plantations managed by small landholders, oil palm plantations belonging to large estates (Murdiyarsa and Wasrin 1995) and abandoned grassland fields, where mainly Alang-alang (*Imperata cylindrica*) grows. We took the samples at 27 sites; seven natural or logged-over forests, three cinnamon (*Cinamum burmanii*) plantations, five oil palm plantations, seven rubber plantations, and five Alang-alang grassland fields. The 'logged-over forest' was defined as forest that was selectively cut and even had a significant amount of aboveground biomass. By the status of this logged-over forest, it is more adequate to categorize it in natural forest rather than in afforested forest, so we categorized the primary and logged-over forest into a forest (F). The location of and the general information about each site are shown in Figure 1 and in Table 1, respectively. We divided the rubber plantation sites and the oil palm plantation sites into two groups. One group included rubber and oil palm plantations more than 10 years old, labeled old rubber (oR) and old oil palm (oO), respectively. The other group included young rubber (yR) and oil palm plantations (yO) less than 10 years old. The total number of sampling sites categorized by soil type and land-use type appears in Table 2.

General land-use history and management in this region

The lowland area was cleared from natural forests and burned for transmigration area in the 1980s. Until 1987, the area was planted with food crops such as maize, upland rice, cassava, soybean and peanuts. However, the yield of the crops was low even though some fertilizers and agriculture lime (calcite; $CaCO_3$) had been applied. Therefore in the 1990s, the transmigration farmers and a private company introduced oil palm in this area, facilitated by the government. In order to speed up the process of clearing land for oil palm plantation, heavy equipment (backhoe, trailer, etc.) was used to uproot the residual trunks and tree branches which were then burned (A. Iswandi, personal communication). As a result of these measures, most of the top soil disappeared and the soil was susceptible to erosion through rainfall. Therefore, for young oil palm up to the age of four years, legume cover crops (such as *Centrosema pubescens*, *Crotalaria juncea*, *Siratro* spp. etc.) were planted not only to protect soils from erosion, but also to increase soil fertility through N_2 fixation. Fertilizers (N, P, K) were regularly added twice a year to the oil palm. Alang-alang grassland was the area of the transmigration farmers who did not take part in the oil palm program or the rather newly cleared forests but abandoned by the farmers. The farmers did not plant food crops because of the low productivity. With the small-holder rubber plantations originating from cleared forest, the residual trunk, twig etc. were burned, and then they grew upland rice without fertilizer and at the same time rubber trees were planted. Upland rice usually was planted up to three growing seasons until the rubber canopy covered the land surface. In cinnamon plantation, farmers never used fertilizers.

Flux measurement

The CO_2 , CH_4 , and N_2O fluxes were measured using a static chamber method. The seven chambers, PVC tubes 0.25 m in diameter and 0.15 m in length, were inserted into the surface soil at each site to a depth of at least 1 cm. After sealing the chambers with PVC tops vented, we took three gas samples of 40 ml from the chamber at times 0, 10, and 20 min with a disposable syringe and then pushed the collected samples over the atmospheric pressure into glass vials of 30 ml with butyl rubber stoppers, which had been evacuated beforehand in the laboratory. We transported the glass vials to our laboratory in Japan where we analyzed

Table 1. Sampling sites description.

Site label	Site name	Vegetation type	Land-use category in this study ^a	Latitude	Longitude	Elevation (m)	Slope	Soil type
F1	Jambi	Logged over forest	F	S01°05'06"	E103°33'46"	0	6°	Udults
F2	Balai Jaya	Logged over forest	F	S01°47'08"	E102°05'47"	ND ^b	35°	Ultisols
F3	Rantau Duku	Logged over forest with old rubbers	F	S01°36'33"	E101°59'06"	110	22–24°	Ultisols
F4	KM31 Teluk Bengkuang	Logged over forest	F	S01°32'49"	E101°47'01"	180	24°	Ultisols
F5	Sungai Ulak, Bangko	Logged over forest	F	S02°01'01"	E102°18'34"	100	10°	Ultisols
F6	Juju Kluru	Primary forest	F	S02°10'48"	E101°31'10"	870	15.5°	Andisols
F7	Bukit Genan Tujuh	Primary forest	F	S01°42'40"	E101°22'13"	1540	17–31°	Andisols
C1	Desa Lempur	Cinnamon plantation	C	S02°13'12"	E101°30'42"	1060	8°	Andisols
C2	Punca Limau Saring	Cinnamon plantation mixed with various vegetation	C	S02°03'20"	E101°21'32"	1160	12°	Andisols
C3	Telun Berasap	Cinnamon plantation	C	S01°41'56"	E101°20'40"	1410	0°	Andisols
R1	Jambi	Rubber plantation forest more than 10 years	oR	S01°42'00"	E103°27'45"	70	0°	Udults
R2	Kuamang Kunin	Rubber plantation forest more than 20 years	oR	S01°35'38"	E102°16'39"	ND ^b	0°	Ultisols
R3	Sungai Buluh	Rubber plantation forest (approximately 5–7 years)	yR	S01°32'46"	E102°10'04"	70	0°	Entisols
R4	Rendal village	Rubber plantation forest more than 15 years	oR	S01°42'15"	E102°10'21"	90	0°	Ultisols
R5	Mentawak, Bangko	Rubber plantation forest more than 10 years	oR	S01°59'56"	E102°17'16"	150	0°	Ultisols
R6	Sungai Manau	Rubber mixed with natural vegetation (10–15 years)	oR	S02°10'39"	E101°52'26"	280	35°	Ultisols
R7	Pulaupandan	Rubber plantation forest (< 10 years)	yR	S02°08'30"	E101°32'22"	820	0.5°	Andisols
O1	Simpangmersam	Oil palm plantation (approximately 5 years)	yO	S01°35'39"	E102°50'09"	ND ^b	<1°	Udults
O2	Babako	Oil palm plantation (approximately 15 years)	oO	S01°29'17"	E102°15'02"	70	0°	Ultisols
O3	Sungai Buluh	Oil palm plantation (approximately 3–5 years)	yO	S01°32'38"	E102°09'53"	50	0°	Entisols
O4	Bukit Apit	Oil palm plantation more than 15 years	oO	S01°43'57"	E102°12'06"	100	2.5°	Inceptisol(?)
O5	Karang Anyar, Bangko	Oil palm plantation (approximately 3 years)	yO	S02°04'25"	E102°26'39"	110	0°	Ultisol
A1	Kuamang Kunin	Alang-alang among agricultural and forest area	A	S01°36'19"	E102°19'30"	ND ^b	0°	Ultisols
A2	Seanamat	Alang-alang	A	S01°29'30"	E102°13'39"	70	4°	Ultisol
A3	Sungai Buluh	Alang-alang 3 months after slash-and-burn	A	S01°30'53"	E102°08'05"	100	5°	Ultisols
A4	Sungai Musawan, Bangko	Alang-alang	A	S02°04'00"	E102°17'54"	100	0°	Ultisol
A5	Sungai Ning	Alang-alang	A	S02°03'53"	E101°21'56"	1140	8°	Andisols

F, forest; C, cinnamon; oR, old rubber; yR, young rubber; oO, old oil palm; yO, young oil palm; A, Alang-alang. ^bNot determined.

Table 2. Number of plots in each soil type and land-use.

		Land-use type ^a							Total
		F	C	oR	yR	oO	yO	A	
Soil type	Udults	1	0	1	0	0	1	0	3
	Other Ultisols and Entisols	4	0	4	1	2	2	4	17
	Andisols	2	3	0	1	0	0	1	7
	Total	7	3	5	2	2	3	5	27

^asee Table 1 for the land-use codes.

the gas concentrations with two gas chromatographs, a Shimadzu GC-9A and a Shimadzu GC-14A. The former was equipped with a thermal conductivity detector for CO₂, and a flame ionization detector for CH₄, and the latter with an electron capture detector and a pre-cut system for N₂O. The standard calibrations of CH₄, CO₂ and N₂O were made using standard gases of 2.01 $\mu\text{l CH}_4 \text{l}^{-1}$, 1994 $\mu\text{l CO}_2 \text{l}^{-1}$, and 0.3 $\mu\text{l N}_2\text{O l}^{-1}$ (Sumitomo Seika Chemicals Co.), respectively. The contamination and leakage of gases in the vials by the transport are negligible as the result of a test presented in Japan. We calculated the flux by the slope of gas concentrations with the sampling times. The temperatures in the chamber, in the ambient air (1 m height above the ground), and in the soil (2 cm and 10 cm depth each) were measured with a temperature sensor (Sato Co., SK-1250MC). For each individual chamber flux measurement, we calculated the 90% confidence interval, and defined the minimum detectable flux as that flux at which > 67% of the confidence intervals did not include zero (Hutchinson and Livingston 1993; Verchot et al. 1999). The minimum detectable N₂O flux was 5.0 $\mu\text{g N m}^{-2} \text{h}^{-1}$.

Soil gas sampling

Soil gas samples were taken with a stainless steel tube (3 mm outer diameter and 1 mm inner diameter) at the soil surface and at depths of 5, 10 and 20 cm. Three samples were taken from each site. The gas concentration was analyzed with the method used for flux measurement.

Soil sampling and analysis

We collected two soil samples per site. One was a disturbed sample for chemical and biochemical analyses, and the other was a volumetric sample for physical analysis. Seven replicates of both types of samples were taken at a depth of 0–5 cm at each site in prox-

imity to the chamber used for gas flux measurement, but at least 30 cm apart from every other chamber. The seven replicates of disturbed soil samples for the chemical and biochemical analyses were mixed thoroughly and employed for the following experiments. To minimize changes in inorganic nitrogen content caused by fast nitrogen mineralization and nitrification, we extracted the inorganic nitrogen at the hotel using a 2 M KCl solution on the same day the sample was taken, and later performed an analysis in the laboratory. The residual disturbed soil samples were passed through a 2 mm mesh sieve, and stored in a refrigerator at 4 °C. We measured soil pH (H₂O) with 10 g soil in 25 ml deionized water using a glass electrode (Horiba, F-22). Total carbon and nitrogen were determined using an NC analyzer (Sumitomo Chemical Co., NC-800). The available phosphate content was measured using the Bray II method (Olsen and Sommers 1982). The microbial biomass carbon (C_{BIO}) was measured by the chloroform fumigation extraction method (Vance et al. 1987) using a TOC analyzer (Shimadzu TOC-5000). With the solution, we determined the nitrogen content using the peroxydisulfate oxidation method and calculated the microbial biomass nitrogen (N_{BIO}) (Sakamoto and Hayashi 1999). The ammonium and nitrate concentrations were determined using a flow-injection analyzer (Tecator, Aquatec 5400 analyzer). The net nitrogen mineralization and nitrification rates were measured by the aerobic incubation method (Hart et al. 1994) at 25 °C for 8 weeks.

For physical analysis of the soil, seven replicates of a 100 ml sample of volumetric soil were collected with a 100 ml cylindrical sampling core. We mixed the seven replicates (700 ml total) to determine soil bulk density, water content, and the volumetric proportion of solid, liquid and gas phases. The solid phase proportion was calculated by dividing the solid weight by 2.5. The particle distribution was determined by the pipette sampling method (Day 1965).

At each site, we also collected triplicate samples of organic matter from the soil surface within an area of 50 cm² and then weighed this dry matter in the laboratory.

Statistical analysis

Because N₂O flux varies according to soil type, we use only the average value of the flux data of each land-use type without the data from Andisols and Udults to compare the effect of land-use on N₂O fluxes ($n =$

17). Neither the CH_4 flux nor the CO_2 flux differed significantly with soil type, so we used the data of 27 sites to compare the effects of land-use on these gases.

Pasir Mayang Research Site (PMRS), in the north-western part of Jambi province (Ishizuka et al. 2002), furnishes another data set with which to determine the relationship between soil properties and greenhouse gas emissions. To compare the data at PMRS with the data of this study, we calculated the averaged flux values of nine measurements repeated across five sampling plots (P1, P2, L2, R, and Op), in PMRS for September and October only, between September 1997 and March 2002 (Tsuruta et al. unpublished data).

Results

General soil properties (Table 3)

Soil type and soil properties. The properties of Andisols ($n = 7$) were different from those of the other soils ($n = 20$). The soil pH for Andisols (6.18 on average, ranging from 5.66 to 6.85) was higher ($P < 0.001$) than that of other soils (4.52 on average, with a range of 4.10 to 5.12). The average values of total carbon and nitrogen content in Andisols (92 mg g^{-1} and 7.9 mg g^{-1} , respectively) were larger ($P < 0.001$) than those of the other soils (33 mg g^{-1} and 2.5 mg g^{-1} , respectively). The average microbial biomass carbon and nitrogen content in Andisols ($1630 \text{ } \mu\text{g C g}^{-1}$ and $280 \text{ } \mu\text{g N g}^{-1}$, respectively) were larger ($P < 0.001$) than those of the other soils ($740 \text{ } \mu\text{g C g}^{-1}$ and $102 \text{ } \mu\text{g N g}^{-1}$, respectively). The bulk density in Andisols (0.63 Mg m^{-3}) was lower ($P < 0.001$) than that of the other soils (0.94 Mg m^{-3}). The proportion of liquid phase to the whole soil volume in Andisols (51%) is larger ($P < 0.002$) than that of the other soils (34%). Compared to the other soils ($0.60 \text{ } \mu\text{g g}^{-1} \text{ d}^{-1}$), Andisols showed higher ($P < 0.03$) nitrification rate ($1.19 \text{ } \mu\text{g g}^{-1} \text{ d}^{-1}$).

Land-use and soil properties. The soil properties at the cinnamon plantation sites were unlike those of the other types of land-use. Because they were all located in the Andisols areas, the cinnamon plantation sites manifested a relatively higher pH, water content, and proportion of liquid phase, while having a lower bulk density. At the Alang-alang grassland field sites, values were low for soil properties such as the nitrogen mineralization rate, the nitrification

rate, the dry weight of litter layer, the water content and the microbial biomass carbon and nitrogen. These results indicate that the microorganisms in the Alang-alang grassland soils were less active than those in the other land-use types. The oil palm plantation sites had characteristics similar to those of the Alang-alang grassland field sites. At oil palm plantation sites, the bulk density was higher and the proportion of gas phase was lower than that of the other land-use types.

Compared to the other sites (except cinnamon plantation), the forest soil had more microbial biomass carbon and nitrogen, greater nitrogen content, and higher nitrogen mineralization and nitrification rates. The nitrate content, nitrogen mineralization, and nitrification rate of old rubber plantation were all larger than those of young rubber plantation, a fact suggesting that the increase in the microorganisms activity coincided with the growth of rubber trees.

Gas fluxes (Table 4)

The soil temperature at 10 cm depth on Andisols is significantly different from that on other soil types ($P < 0.001$, Table 4), because the areas of Andisols are located above 800 m elevation and mean annual temperature is thought to be lower than that of low-land area. This low soil temperature on Andisols must affect the microorganisms' activity and thus we must consider this effect.

CO_2 . The average CO_2 flux was calculated to be $3.65 \pm 0.85 \text{ g C m}^{-2} \text{ d}^{-1}$ ($n = 27$), with a range of 1.88 to $5.16 \text{ g C m}^{-2} \text{ d}^{-1}$. For forest stands, the average flux was $3.88 \pm 0.50 \text{ g C m}^{-2} \text{ d}^{-1}$ ($n = 7$). Although the CO_2 flux of Andisols ($4.00 \pm 0.57 \text{ g C m}^{-2} \text{ d}^{-1}$, $n = 7$) is relatively larger than that of the other soils ($3.52 \pm 0.90 \text{ g C m}^{-2} \text{ d}^{-1}$, $n = 20$), the difference is not significant (Table 5, $P = 0.204$, by Student's *t*-test). The CO_2 flux at oil palm plantation (2.36 ± 0.22 , $n = 5$) was significantly smaller than those of the other land-use types (Table 6, $P < 0.05$, by ANOVA).

CH_4 . The overall average CH_4 flux across all land-use types equalled $-0.45 \text{ mg C m}^{-2} \text{ d}^{-1}$, with the CH_4 flux of the 27 sites ranging from -1.27 to $1.18 \text{ mg C m}^{-2} \text{ d}^{-1}$. The average flux across all forest stands, $-0.70 \pm 0.35 \text{ mg C m}^{-2} \text{ d}^{-1}$ ($n = 7$), was smaller than those of the other land-use types except for the old oil palm plantation ($-0.75 \pm 0.58 \text{ mg C m}^{-2} \text{ d}^{-1}$, $n = 2$). Of a total of 189 cham-

Table 3. General soil properties.

Plot	Soil ^a	Land-use ^b	pH	Total C	Total N	C/N	NH ₄	NO ₃	N-min ^c	Nitr ^d	Biomass C	Biomass N	SWC ^e	Bulk density	WFPS ^f	Litter	Soil texture		
																	Sand (%)	Silt (%)	Clay (%)
F1	Ud	F	4.32	30.8	2.2	13.8	1.94	3.07	0.50	0.58	651	103	0.35	1.01	59.4	418.5	60.9	17.3	21.9
F2	Ult	F	4.10	60.3	4.1	14.7	7.78	7.76	1.33	1.12	1305	148	0.54	0.69	51.4	502.9	28.8	13.7	57.5
F3	Ult	F	4.81	37.2	3.1	12.1	5.45	2.14	0.68	0.63	970	169	0.11	1.11	22.6	377.6	63.9	7.6	28.5
F4	Ult	F	4.20	25.7	2.5	10.2	5.24	5.11	1.03	1.10	1101	172	0.43	0.93	63.2	193.3	26.0	15.3	58.7
F5	Ult	F	4.30	41.7	2.9	14.5	3.98	8.07	0.90	0.67	1039	124	0.34	0.76	37.8	99.1	43.6	18.2	38.2
F6	A	F	6.85	47.2	4.1	11.4	5.37	1.16	0.67	0.76	1380	271	0.52	0.88	70.3	80.4	33.6	30.4	36.0
F7	A	F	6.06	213.9	16.3	13.1	14.61	4.31	2.36	2.65	3426	553	1.85	0.29	61.9	161.5	34.6	55.6	9.8
C1	A	C	5.66	97.2	9.0	10.7	10.36	2.74	1.20	1.37	1540	283	0.98	0.53	65.3	1924.5	25.2	53.5	21.3
C2	A	C	6.10	44.2	4.0	11.1	6.01	1.18	0.54	0.71	961	170	0.72	0.76	78.8	141.2	20.2	31.4	48.4
C3	A	C	6.49	129.3	11.2	11.6	12.02	4.77	1.73	1.97	1521	265	1.11	0.47	64.5	56.4	44.4	39.3	16.3
R1	Ud	oR	4.16	29.8	2.2	13.2	4.73	4.31	0.50	0.64	616	89	0.34	0.98	55.3	223.4	53.8	15.7	30.5
R2	Ult	oR	4.16	33.0	2.3	14.6	5.50	2.61	0.69	0.66	735	107	0.31	0.95	47.1	631.8	46.4	15.4	38.2
R3	Ent	yR	4.45	18.0	1.3	14.2	3.02	0.50	0.17	0.23	286	41	0.21	1.20	48.0	280.6	78.2	7.9	13.9
R4	Ult	oR	4.47	64.0	4.5	14.1	7.93	4.88	1.51	1.63	1397	166	0.52	0.68	48.2	296.0	13.0	32.0	55.0
R5	Ult	oR	4.27	40.1	3.0	13.2	8.41	1.97	0.99	1.10	861	133	0.44	0.84	55.9	74.7	32.7	11.5	55.8
R6	Ult	oR	4.43	22.9	2.1	10.8	8.38	0.95	0.39	0.50	795	148	0.84	0.75	90.7	402.6	24.3	43.6	32.1
R7	A	yR	6.15	68.9	6.0	11.4	6.05	1.26	0.72	0.84	1568	270	0.82	0.67	75.0	81.7	15.5	59.4	25.1
O1	Ud	yo	5.04	11.5	1.0	11.5	4.41	1.06	0.16	0.33	198	32	0.34	1.16	73.1	173.8	48.5	25.6	25.9
O2	Ult	oO	4.70	24.4	1.8	13.4	4.63	1.54	0.19	0.28	518	74	0.29	1.08	55.0	205.3	51.5	7.3	41.2
O3	Ent	yo	4.63	15.5	1.1	14.0	2.34	0.89	0.26	0.33	309	42	0.16	1.18	35.5	135.6	87.9	7.1	4.9
O4	Inc	oO	4.67	38.2	3.3	11.6	3.02	3.30	0.49	0.60	824	119	0.60	0.89	83.1	50.5	16.2	10.5	73.3
O5	Ult	yo	4.29	42.9	3.1	14.1	2.85	1.15	0.46	0.66	709	101	0.46	0.93	68.7	215.1	10.9	28.2	61.0
A1	Ult	A	4.91	17.6	1.4	13.0	2.00	1.51	0.08	0.21	376	49	0.14	1.05	25.2	136.4	50.7	19.2	30.1
A2	Ult	A	4.77	37.6	2.7	14.1	9.77	2.37	0.29	0.41	640	81	0.58	0.77	64.3	139.9	47.7	15.3	31.0
A3	Ult	A	5.12	25.5	1.9	13.6	13.80	5.77	0.11	0.02	480	30	0.22	0.91	31.6	19.1	40.2	6.8	53.0
A4	Ult	A	4.54	46.5	3.2	14.8	3.22	0.98	0.24	0.37	892	122	0.44	0.87	58.7	105.3	9.5	12.4	77.6
A5	A	A	5.97	40.8	3.0	13.8	3.18	0.46	-0.07	-0.01	1047	151	0.51	0.84	64.8	135.7	8.7	22.8	68.5

^aA; Andisols, Ud; Udupts, Ult; Ultisols except Udupts, Ent; Entisols, Inc; Inceptisols. ^bsee Table 1 for the land-use codes. ^cNitrogen mineralization rate, ^dnitrification rate, ^esoil water content, ^fwater-filled pore space. Units: total C and total N, mg g⁻¹; NH₄ and NO₃, μg g⁻¹; N-min and Nitr, μg g⁻¹ d⁻¹; biomass C, μg C g⁻¹; biomass N, μg N g⁻¹; SWC, kg kg⁻¹; bulk density, Mg m⁻³; WFPS, %; and litter, g m⁻².

Table 4. The average fluxes of three gas species at each site^a.

Land-use ^b		CO ₂		CH ₄		N ₂ O		Soil temperature (°C)
		(g C m ⁻² d ⁻¹)		(mg C m ⁻² d ⁻¹)		(μg N m ⁻² h ⁻¹)		
		Ave.	SD	Ave.	SD	Ave.	SD	
F1	F	3.96	0.85	-0.91	0.20	23.60	17.98	26.0
F2	F	3.17	0.79	-0.71	1.13	9.57	8.09	26.1
F3	F	3.36	0.75	-1.27	0.12	2.52	1.87	26.2
F4	F	4.35	1.87	-0.39	0.33	9.58	8.14	22.9
F5	F	4.19	1.20	-0.49	1.46	12.85	9.09	27.7
F6	F	4.45	1.56	-0.27	0.57	3.22	1.64	20.3
F7	F	3.67	1.04	-0.87	1.21	3.83	3.77	18.6
C1	C	4.15	0.79	-0.99	0.19	1.27	0.67	22.2
C2	C	4.52	0.98	-0.11	0.20	3.52	3.32	18.1
C3	C	3.33	1.24	-0.86	0.34	12.88	23.21	18.8
R1	oR	4.90	0.88	-0.36	0.20	55.82	46.83	27.6
R2	oR	5.16	2.02	1.18	3.54	9.08	8.71	25.9
R3	yR	2.95	1.39	-0.41	0.26	3.13	1.85	26.7
R4	oR	3.87	0.79	-0.19	0.28	19.82	10.11	27.1
R5	oR	3.86	0.61	-0.74	0.80	16.51	14.70	28.3
R6	oR	3.43	1.11	0.15	0.97	1.62	0.81	25.5
R7	yR	4.62	0.80	-0.61	0.29	1.19	1.52	21.5
O1	yO	3.12	1.21	0.11	0.41	28.83	31.16	27.2
O2	oO	1.88	0.48	-1.16	0.21	1.14	1.03	24.3
O3	yO	2.04	0.60	-0.77	0.31	7.68	13.51	26.2
O4	oO	2.24	1.08	-0.34	0.64	4.26	6.34	26.0
O5	yO	2.50	0.50	-0.25	0.26	15.24	16.37	27.2
A1	A	3.94	1.53	-0.15	0.17	1.53	1.51	26.6
A2	A	4.12	2.81	-0.04	1.11	3.39	4.08	25.8
A3	A	3.18	0.45	-0.55	0.22	1.30	1.12	31.1
A4	A	4.26	1.39	-0.85	0.12	0.60	0.68	28.3
A5	A	3.28	1.11	-0.26	0.40	0.13	1.72	17.9

^aMeans of 7 replicates.^bSee Table 1 for the land-use codes.

Table 5. The averaged fluxes of three greenhouse gases in each soil type.

Soil type		Number of sites	CO ₂		CH ₄		N ₂ O	
			(g C m ⁻² d ⁻¹)		(mg C m ⁻² d ⁻¹)		(μg N m ⁻² h ⁻¹)	
			Ave.	SD	Ave.	SD	Ave.	SD
Andisols		7	4.00	0.57	-0.57	0.35	3.7	4.3
Ultisols	Udults	3	3.99	0.89	-0.39	0.51	36.1	17.3
	others ^a	17	3.44	0.91	-0.41	0.56	7.0	6.1
Total		27	3.65	0.85	-0.45	0.50	9.4	12.0

^aIncluding two Entisols sites.

bers (7 chambers × 27 sites), 32 chambers showed positive CH₄ flux; moreover, all land-use types had some chambers showing a positive flux. We observed no significant difference in CH₄ flux between Andisols and the other soils (Table 5).

N₂O. The overall average across all sites was 9.4 μg N m⁻² h⁻¹, with a range of 0.13 to 55.8 μg N m⁻² h⁻¹. The average flux of N₂O on forest stands was 9.3 ± 7.4 μg N m⁻² h⁻¹ (*n* = 7). N₂O flux exhibited relatively greater heterogeneity than did CO₂ and CH₄ fluxes. At some sites there

Table 6. The averaged CO₂ and CH₄ flux of each land-use type.

Land-use type ^a	Number of cases	CO ₂ flux		CH ₄ flux	
		Average	S.D.	Average	S.D.
F	7	3.88	0.50	-0.70	0.35
C	3	4.00	0.61	-0.65	0.47
oR	5	4.24	0.74	0.01	0.73
yR	2	3.78	1.18	-0.51	0.14
oO	2	2.06	0.26	-0.75	0.58
yO	3	2.56	0.54	-0.30	0.44
A	5	3.76	0.49	-0.37	0.33
Total	27	3.65	0.85	-0.45	0.50

^aSee Table 1 for the land-use codes.

were hot spots that produce high N₂O fluxes (data not shown). The N₂O fluxes of Udults (23.6, 55.8 and 28.8 $\mu\text{g N m}^{-2} \text{h}^{-1}$ for F1, R1 and O1, respectively) were higher than those of the other soils (Table 5). The N₂O fluxes for the old rubber (except R1, 11.8 \pm 8.1 $\mu\text{g N m}^{-2} \text{h}^{-1}$, $n = 4$) and for the young oil palm plantation (except O1, 11.5 \pm 5.3 $\mu\text{g N m}^{-2} \text{h}^{-1}$, $n = 2$) were relatively larger than those of the other land-use types (Table 7). Alang-alang grassland field (1.39 \pm 1.25 $\mu\text{g N m}^{-2} \text{h}^{-1}$, $n = 5$) and young rubber plantation (2.16 \pm 1.37 $\mu\text{g N m}^{-2} \text{h}^{-1}$, $n = 2$) showed relatively lower N₂O fluxes than did the other land-use types (Table 7).

Soil gas. In almost all profiles, the CH₄ concentration decreased and the N₂O and CO₂ concentrations increased at greater soil depths. The typical patterns of each gas concentration with depth are shown in Figure 2. High CH₄ concentrations, greater than 1.8 $\mu\text{m}^3 \text{m}^{-3}$, were observed at depths of 5 cm (F5, O1, A1 and C3), 10 cm (F4, F5 and A3), and both 5 and 10 cm (R4, R6). At oil palm plantation sites, the disparity between gas concentrations at the surface and at 5 cm depth was greater than those at the other land-use types (Figure 2).

Comparison of soil properties and gas fluxes between PMRS and the 27 sites in this study

The summary of soil properties and averaged gas fluxes in PMRS is shown in Table 8. The soil at PMRS revealed significant differences from the soils at the 27 sites in this study. The soil at PMRS had relatively lower values in water content, nitrification rate, and microbial biomass nitrogen, while at the same time having higher values in ammonium nitrogen content, dry weight of the litter layer, and gas phase proportion

Table 7. The averaged N₂O emission of each land-use type^a.

Land-use type ^b	Number of cases	N ₂ O flux	
		Average	S.D.
F	4	8.63	4.35
oR	4	11.76	8.12
yR	1	3.13	
oO	2	2.70	2.20
yO	2	11.46	5.35
A	4	1.70	1.19
Total	17	7.05	6.11

^aWithout the data on Andisols and Udults.

^bSee Table 1 for the land-use codes.

($P < 0.05$, by ANOVA). This result indicates that at PMRS the stress to the microorganisms arising from dry soil conditions leads to the suppression of microbial activities such as nitrification and decomposition of litter layer, in turn resulting in the accumulation of ammonium and of litter layer.

The CO₂ flux in PMRS (1.87 \pm 0.34 $\text{g C m}^{-2} \text{d}^{-1}$) was significantly smaller than the overall CO₂ flux of the 27 sites in this study ($P < 0.001$ by Student's t -test). The N₂O flux at PMRS (2.9 \pm 1.7 $\mu\text{g N m}^{-2} \text{h}^{-1}$) is lower than the overall value of the 27 sites in this study (7.0 \pm 6.1 $\mu\text{g N m}^{-2} \text{h}^{-1}$, $n = 17$, except for those at the sites with Andisols and Udults). The average CH₄ flux in PMRS (-0.21 \pm 0.25 $\text{mg C m}^{-2} \text{d}^{-1}$) was larger than the average of the 27 sites in this study (-0.45 \pm 0.50 $\text{mg C m}^{-2} \text{d}^{-1}$).

Discussion

N₂O emissions

The intensity of N₂O flux on forest stands, 9.3 $\mu\text{g N m}^{-2} \text{h}^{-1}$ ($n = 7$) (equivalent to 0.81 $\text{kg N ha}^{-1} \text{y}^{-1}$), belongs to the lowest group in the humid tropical forest, which ranged from 0.01–7.68 $\text{kg N ha}^{-1} \text{y}^{-1}$ (Breuer et al. 2000). This relatively low N₂O flux in Southeast Asia was firstly observed in PMRS (Ishizuka et al. 2002), which had a range of 1.5 to 7.9 $\mu\text{g N m}^{-2} \text{h}^{-1}$. According to the results of this study, the data at PMRS belongs to the group of smaller N₂O fluxes in Jambi Province, but the N₂O fluxes in Jambi Province are still relatively lower than those of other humid tropical forest, such as Australia, Costa Rica, and the Amazon (see summarization by Breuer et al. 2000).

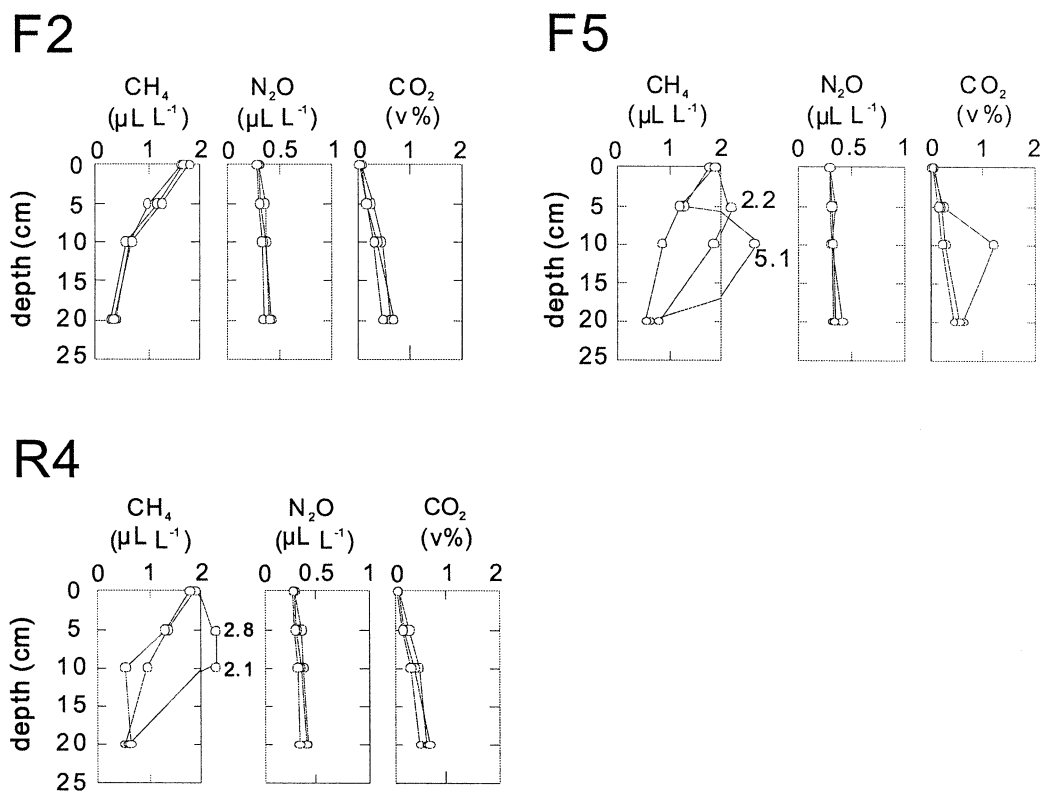


Figure 2. The profile of soil gas concentration at F2 (upper left), F5 (upper right), and R4 (lower left). The data are shown in triplicate profiles for each site. The profile like at F2 was normally observed, while the kind of profile like at F5 and R4, which showed high CH_4 concentration at 5 cm and/or 10 cm depth, was irregularly observed.

The N_2O fluxes differed according to soil type. We observed the highest emissions under wet conditions, such as those at F1, R1 and O1. Furthermore, the N_2O fluxes in PMRS, with its relatively drier conditions, were lower than those of the other sites. These results indicate that in this area the N_2O fluxes are mainly determined by soil moisture which affected both the nitrification and denitrification rates. According to the hole-in-the-pipe model, WFPS affects the ratio of N_2O and NO . The lower WFPS, the higher the ratio of NO to N_2O (Davidson et al. 2000a). We calculated the relationship between the sum of NO and N_2O emissions estimated by WFPS (Davidson et al. 2000a) and nitrification rate, but there was no significant relationship ($R = 0.125$, $\alpha = 0.54$). The sites having less than 20% or higher than 75% WFPS had low N_2O fluxes (Figure 3), this result suggesting that in the former NO and the latter N_2 is the dominant gas as nitrogenous gas loss. The fluxes between 20% and 75% WFPS scattered, this result suggesting that WFPS is not a dominant factor to control N_2O emission in these soils.

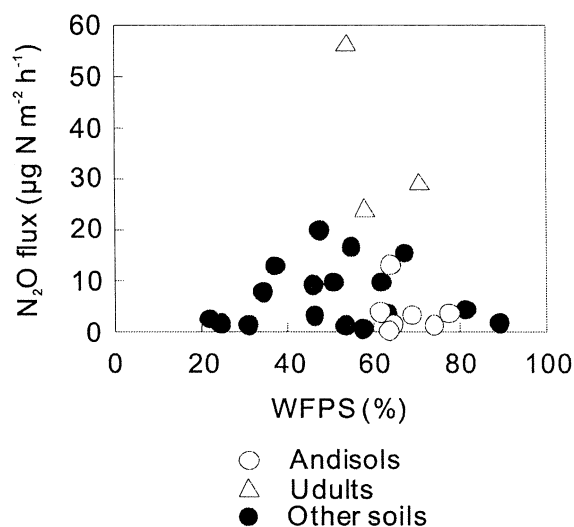


Figure 3. The relationship between soil WFPS and N_2O flux at 27 sampling sites in each soil type.

The correlation coefficient, except in the cases of Udufts (R1, F1 and O1) and Andisols, was compar-

Table 8. Summary of soil characteristics at Pasir Mayang at 0–5 cm depth and gas fluxes^a.

		Plot name				
		P1	P2	L2	Op	R
Land-use type ^b		F	F	F	A	yR
pH		4.38	3.91	3.73	4.43	4.59
Total C	(mg g ⁻¹)	21.2	21.4	23.0	33.5	19.5
Total N	(mg g ⁻¹)	1.1	1.3	1.4	2.2	1.9
C/N		19.1	16.5	15.9	15.5	10.0
NH ₄	(μg g ⁻¹)	7.9	7.2	6.0	10.6	10.5
NO ₃	(μg g ⁻¹)	3.3	1.6	1.6	1.7	1.7
N-min ^c	(μg g ⁻¹ d ⁻¹)	0.26	0.52	0.43	0.47	0.29
Nitr ^d	(μg g ⁻¹ d ⁻¹)	0.03	0.26	0.30	0.27	0.01
Biomass C	(μgC g ⁻¹)	936	770	712	628	221
Biomass N	(μgN g ⁻¹)	55	79	73	54	29
SWC ^e		0.149	0.174	0.161	0.233	0.405
Bulk density		1.00	0.75	0.82	0.80	0.76
WFPS ^f		23.2	24.1	25.7	33.0	42.9
Litter		972	ND ^h	1518	1221	833
Soil texture	Sand (%)	66.0	ND ^h	73.7	64.6	32.6
	Silt (%)	15.8	ND ^h	15.2	10.8	43.3
	Clay (%)	18.2	ND ^h	11.2	24.6	24.0
CO ₂ flux ^g		1.69	2.21	2.00	1.38	2.10
CH ₄ flux ^g		-0.24	0.18	-0.50	-0.14	-0.34
N ₂ O flux ^g		2.60	4.33	4.93	1.71	0.86

^aSummarized data of Ishizuka et al. (2002) with additional data at PMRS.

^bSee Table 1 for the land-use codes.

^cNet nitrogen mineralization rate.

^dNet nitrification rate.

^eSoil water content.

^fWater filled pore space.

^gThe averaged flux for September and October only between Sept. 1997 and March 2002.

^hNot determined.

able with that in the previous report (Figure 4, Matson and Vitousek 1987; Keller et al. 1988; Livingston et al. 1988; Ishizuka et al. 2000), calculated by the following equation:

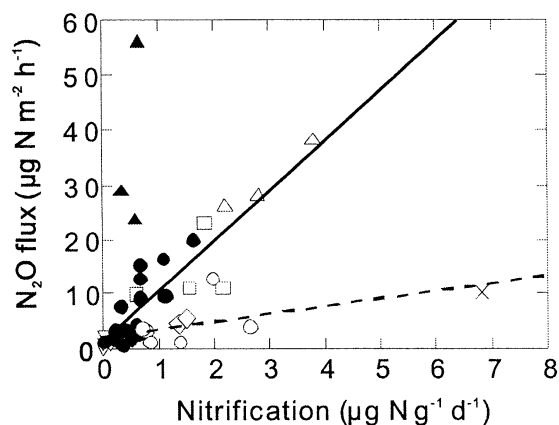
$$F = 9.256 \times NR + 0.4993 (R^2 = 0.7822) \quad (1)$$

where F is N₂O flux (μg N m⁻² h⁻¹) and NR (μg N g⁻¹ d⁻¹) is nitrification rate. This result suggests that in tropical forests throughout the world, nitrification is an important rate limiting process to cause N₂O emission not only from the nitrification process but also from the denitrification process by providing nitrate as the substrate. It also suggests that the low N₂O fluxes in these sites result from the low net nitrification rates, whose average, 5.3 ± 4.2 μg N/g/7d, was relatively lower than at the other sites (net nitrification rate in Figure 4 in Davidson et al. 2000a). There are, however, two exceptions in the relationship between the N₂O flux and the nitrific-

ation rate. The first is the sites on Andisols, which had a much lower correlation coefficient. The coefficient for Andisols, including Japanese Andisols (Ishizuka et al. 2000), was one-seventh of that of the other soils (Figure 4), and is expressed as the following equation:

$$F_A = 1.377 \times NR_A + 1.941 (R^2 = 0.4187) \quad (2)$$

where F_A (μg N m⁻² h⁻¹) and NR_A (μg N g⁻¹ d⁻¹) are the N₂O flux and the nitrification rate in Andisols, respectively. One reason for this low correlation coefficient is that the N₂O flux on Andisols was measured under relatively lower temperature. The mean temperature of these Andisols (including 16.4°C with Japanese Andisols; Ishizuka et al. 2000) was 19.2°C, which was 7.4°C lower than that of the other soils. If the bias by this lower temperature exceeded a factor of 7, the correlation coefficient would be nearly equal to that of other soils in Equation 1. But a factor of 7 in the difference of 7.4°C seems to be very large for such



previous data

- △ Costa Rica (Matson and Vitousek 1987)
- Amazonia (Livingston et al. 1988; Keller et al. 1988)
- ▽ Hawaii (Matson and Vitousek 1987)
- × Japanese Andisol (Ishizuka et al. 2000)
- ◇ Japanese Inceptisols (Ishizuka et al. 2000)

this study

- Andisols
- ▲ Udults
- Other soils

Figure 4. The relationship between nitrification rate and N_2O flux throughout the world. The solid line indicates the regression incorporating all data except Andisols and Udults (R1, F1, and O1) in tropical forests. The dashed line indicates the regression using the data of Andisols, including the data of Japanese Andisol.

microbial process; there may be another reason for the lower N_2O fluxes in these Andisols. Another important nitrogenous gas, NO , could possibly account for the main part of gaseous loss of nitrogen from Andisols (Akiyama et al. 2000). But this supposition is questionable, however, because the WFPS of these Andisols, ranging from 61.5% to 77.5% (Figure 3), is the ideal value for N_2O to be the dominant gas in gaseous nitrogen loss (Davidson et al. 2000a). In any case, we need more intensive research to clarify the mechanisms of N_2O emission from Andisols.

The second exception in the relationship between the N_2O flux and the nitrification rate is the high emission rates at R1, F1 and O1 (Table 5, Figure 4), where the observed N_2O flux exceeds the value calculated by regression Equation 1. This result indicates that in some places with wet conditions, such as Udults, the N_2O was derived from the denitrification processes.

CH_4 uptake/emission

Our results on CH_4 uptake rate ($0.70 \pm 0.35 \text{ mg C m}^{-2} \text{ d}^{-1}$, $n = 7$) in forest stands were comparable with those in the previous report ($0.79 \pm 0.12 \text{ mg C m}^{-2} \text{ d}^{-1}$; Potter et al. 1996). The estimate based on soil texture classification by Dörr et al. (1993), designated as medium or coarse for the soils in this study, ranged from 0.33 to $1.07 \text{ mg C m}^{-2} \text{ d}^{-1}$, suggesting that the estimate of CH_4 uptake rate in Southeast Asia is reasonable.

CH_4 emission from unknown sources may have an impact on these flux values, because 17% of total chambers showed positive flux. The sudden increase of CH_4 concentrations in the soil gas profiles (for example, at the depth of 5 and 10 cm at F5 (Figure 2)) suggests the presence of a CH_4 source at subsurface soil. At F4 and F5, the CH_4 concentration at the depth of 5 cm was smaller than that in the ambient air, for a profile having a high CH_4 concentration at a depth of 10 cm. This fact suggests that the emitted CH_4 at 10 cm depth was partly oxidized by the methanotrophs in the upper soil layers, thus resulting in the negative CH_4 flux at the soil surface. It follows from this result that the negative fluxes (an indication of CH_4 uptake by the soil), in certain cases, were also possibly affected by CH_4 emissions in the layer below. At R4 and R6, the CH_4 concentration at the depth of 5 cm was larger than that in the ambient air for the same profile, showing high CH_4 concentration at the depth of 10 cm. This pattern suggests that the oxidation potential in the surface layer is insufficient for oxidizing the entire quantity of CH_4 emitted in the layer below.

Possibly owing to this 'noise' of CH_4 source, the relationship between soil properties and CH_4 uptake rate was obscure. Many researchers have found a good correlation between CH_4 uptake rate and soil properties, for example ammonium content (King and Schnell 1994), diffusion coefficient (Keller and Reinert 1994), and clay content (Ishizuka et al. 2002), but we did not find a good correlation with soil properties in this study (for example, the correlation coefficient with ammonium nitrogen, diffusion coefficient estimated by pore space, and clay content was -0.133 , 0.135 , and -0.242 , respectively).

One plausible source of CH_4 in the subsurface layer was termites, which are known as an important source of CH_4 (Cicerone and Oremland 1988). Assuming that the CH_4 emission in subsurface soils mainly derived from termites, an isotope ratio such as $\delta^{13}C$ would undoubtedly be an effective tool for

future research to identify the ratio of CH₄ emission from termites to the oxidation by the soil (Sugimoto et al. 1998). This would help us better understand the relationship between CH₄ uptake rate by soils and soil properties, such as the soil texture or the proportion of soil gas phase.

We can present plausible explanations as to why the CH₄ fluxes in PMRS were lower than those in this study: termite density is high, especially in primary forest, in PMRS. Positive CH₄ flux was invariably detected at the forest sites in PMRS, although the soil had relatively high potential to oxidize CH₄ (Tsuruta et al., unpublished data). If the impact of termites in PMRS was greater than that in the area outside of PMRS, then the value for the CH₄ uptake rate in PMRS was low. It is consistent to assume that high CH₄ emission from termites in PMRS increased the soil CH₄ concentration and reduced apparent CH₄ uptake rate. High positive CH₄ fluxes of more than 2 mg C m⁻² d⁻¹ were irregularly observed at old rubber plantation and forest stands in this study; the result implies that the density of termites depends on the stability of land-use or the aboveground biomass of the trees. According to this hypothesis, the forest in PMRS had not been affected by human activity for a long time and this stability of land-use may contribute to the high density of termites in PMRS. The effect of termites on global warming was not considered significant with regard to methane production worldwide (Eggleton et al. 1999; Verchot et al. 2000), but our result, that even the sites showing negative CH₄ flux were possibly affected by termites, seems to impose that the termite effect to CH₄ uptake rate in such terrestrial ecosystems is more significant.

CO₂ emission

The CO₂ emission rate was comparable with that of a previous report (Raich and Schlesinger 1992). The estimated values for this study, ranging from 3.25 to 3.86 g C m⁻² d⁻¹, can be obtained with the following equation (Raich and Schlesinger 1992):

$$SRA = 9.26 \times Ta + 0.0127 \times Ta \times Pa + 289, \quad (3)$$

where *SRA* (g C m⁻² y⁻¹) is the annual soil respiration rate, *Ta* (°C) is the mean annual air temperature (25 °C in this area) and *Pa* (mm) is the mean annual precipitation (from 2100 to 2800 mm for this area). Lower values, ranging from 1.2 to 2.2 g C m⁻² d⁻¹, were reported in the previous report on PMRS (Ishizuka et al. 2002), but our study suggests that the value obtained

at PMRS showed lower emission rates because of the dry soil conditions. The value at PMRS is one of the variations of this area, and the averaged flux in this province should be raised to 3.3 g C m⁻² d⁻¹, a figure which supports the results of the previous report (Raich and Schlesinger 1992).

The effect of temperature and soil water content is not clear. There is no apparent relationship between soil water content and CO₂ flux (Figure 5). One reason is that we cannot produce matric potential data to compare the relationship as shown in the previous report (Davidson et al. 2000b). The sites on Andisols had low soil temperature (from 18 °C to 23 °C with an average of 19.8 °C), but the CO₂ flux is relatively larger than that of the other sites having high soil temperature (from 23 °C to 31 °C with an average of 26.6 °C). Because the CO₂ fluxes on Andisols may reflect this relatively cool temperature, the potential CO₂ flux on Andisols under the same temperature as the lowland area may be higher than that of the other soil types. The effects of temperature and soil water content were also confounded in these soils with different soil type and different soil temperature.

Chronosequence analysis with land-use/cover change

We can present some hypotheses about the effect of land-use change, conversion of forest to rubber plantation, oil palm plantation, and abandoned grassland field by a chronosequence analysis under the assumption that there is not so much seasonal fluctuation in each flux as shown in PMRS (Tsuruta et al., this issue). Because these hypotheses are obtained from one sampling at one point in time, the hypothesis must be confirmed by more frequent sampling in the future. This study may be the first report to deal with the conversion from tropical forests to rubber plantation and oil palm plantation.

The relatively low N₂O fluxes at the young rubber plantation (Table 7) suggest that the N₂O flux decreased after deforestation when the rubber trees had not yet matured. The N₂O fluxes at the old rubber plantation were larger than those of forest stands (Table 7), but this difference was not significant, suggesting that rubber plantation may cause only minor increase in N₂O flux in the long term, i.e., more than 10 years. The decrease of N₂O fluxes after deforestation is basically comparable to that in the study of Verchot et al. (1999), in which active and degraded pasture and a secondary forest had lower emission than a primary forest; but the full recovery of N₂O

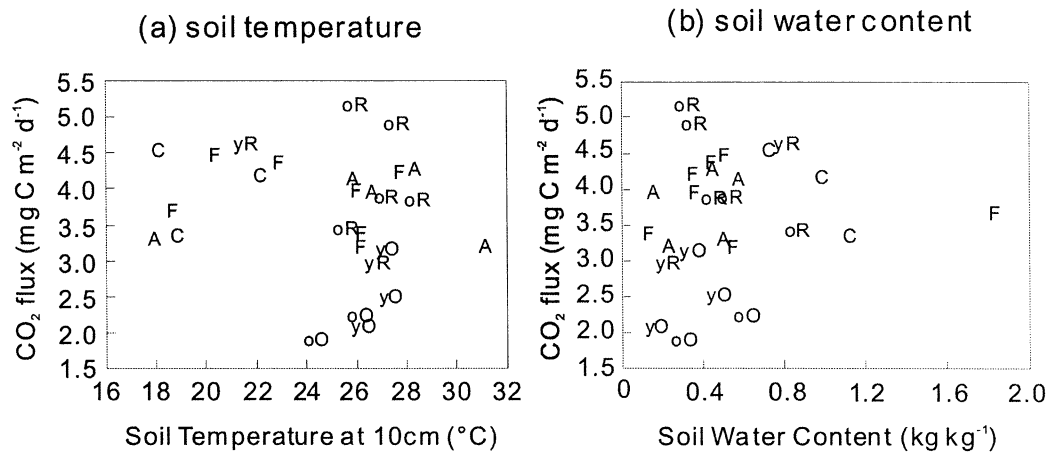


Figure 5. The relationship between soil temperature (a) and CO₂ flux and between soil water content and CO₂ flux (b). Plotting symbols indicate the land-use code (see Table 1). The group of lower soil temperature less than 23 °C in (a) belongs to the sites in the mountainous area above 800 m elevation, which are on Andisols.

emission in a few decades to the level similar to that of the forest stands was not comparable with their result. Our result suggests that in the long term conversion from tropical forest to rubber plantation could have little effect on N₂O emission. Of course, because deforestation and/or biomass burning should have a pronounced impact on N₂O emissions in the short term (Ishizuka et al. 2002) and in the long term (Keller et al. 1993), and the future usage of the rubber plantation site is still obscure, we have to consider the total effect of the land-use change from forests to rubber plantation.

The CH₄ uptake rate for the old rubber plantation (Table 6) was largest in all land-use types. Positive CH₄ flux was observed in 7 of 35 chambers, with highest CH₄ emission of 8 mg C m⁻² d⁻¹. The most frequent range was -1.0 to -0.5 mg C m⁻² d⁻¹; 15 chambers belonged to this range. This result indicates that the growth of rubber trees coincides with the increase of a hot spot of CH₄ emission. It is possible to assume the increase of this hot spot by the increase of termite density, but we have no data to support this. However, the land-use change from forest to rubber plantation might cause little decrease in CH₄ uptake rate in the long term.

Young oil palm plantation had a higher N₂O flux than did forest stands (Table 7), while old oil palm plantation had a value lower than that of forest stands. This high N₂O emission from young oil palm plantation is considered as the result of fertilizer and nitrogen fixation by the legume crops in young oil palm like the legume-rich forest (Davidson et al. 2000a). The

disappearance of legume crop and increase of nitrogen uptake by old oil palm may result in the low N₂O flux in old oil palm plantation. The low N₂O flux for old oil palm plantation (Table 7) suggests that in the long term, i.e., more than 10 years, the N₂O flux will decrease at the oil palm plantation.

The change in the CH₄ uptake rate following the conversion of forest to oil palm plantation exhibited a trend opposite to that of rubber plantation (Table 6). The CH₄ uptake rate decreased for several years after oil palm plantation, although the growth of oil palm coincided with an increase in the CH₄ uptake rate. The change in land-use from forest to oil palm plantation might produce little change in CH₄ uptake rate in the long term (more than 10 years).

The CO₂ fluxes for young and old oil palm plantation were the smallest among all land-use types (Table 6), a finding that suggests that the conversion from any land-use to oil palm plantation will decrease the CO₂ flux. At oil palm plantation, the soil was compacted by intense human activities, giving the soil relatively higher bulk densities. This increased density resulted in less undergrowth and litter layer at oil palm plantation. In addition to the land reform by heavy equipments before oil palm plantation, the lack of the respiration of undergrowth and litter layer makes the CO₂ efflux from the soil surface smaller than that from the other land-use types.

The relatively low N₂O fluxes and CH₄ uptake rate for the Alang-alang grassland fields (Tables 6 and 7) suggest that the conversion of forest to Alang-alang grassland field would cause the decrease in the N₂O

flux and CH₄ uptake rate. The CO₂ flux at the Alang-alang grassland field was the same as the flux at the forest stands, a fact suggesting that the conversion from forests to the Alang-alang grassland field will have little effect on CO₂ flux.

Conclusions

Measurements of the fluxes of three greenhouse gases in Jambi Province, Sumatra, Indonesia were updated. The CO₂ flux ranged from 1.38 to 5.16 g C m⁻² d⁻¹ (3.65 g C m⁻² d⁻¹ on average), a range twice as large as the value previously reported for this area, but comparable with that in the report by Raich and Schlesinger (1992). The CH₄ flux ranged from -1.27 to 1.18 mg C m⁻² d⁻¹ (-0.70 mg C m⁻² d⁻¹ on average for forest stands), values in the range of the previous estimates by Dörr et al. (1993). A significant reduction in the CH₄ uptake rate arose from CH₄ emissions from unknown source, possibly termites. The N₂O flux ranged from 0.13 to 55.8 μg N m⁻² h⁻¹ (9.3 μg N m⁻² h⁻¹ on average for forest stands), which was larger than the value previously reported for this area, but was relatively smaller than those of other humid tropical forests. The low N₂O flux can be attributed to both the low nitrification rate in this area, and the low proportion of released N₂O to measured nitrification in Andisols. We presented some hypotheses about the effect of land-use change, but because these hypotheses were obtained from one sampling at one point in time, further tests are required for verification.

Acknowledgements

This study was managed under the project titled 'The impact of land-use/cover change in terrestrial ecosystems of tropical Asia on greenhouse gas emissions' in the 'Global Environmental Research Program' supported by a grant from the Ministry of the Environment, Japan. We thank Mr Zuhdi and Mr Ermadani of Jambi University for their kind assistance in the field work. We extend our thanks to the staffs at ICRAF in Muarabungo and at IPB in Bogor. We also thank the assistants, Ms Banzawa, Ms Yoshizawa, Ms Matsuoka in NIAES, Ms Takeuchi in FFPRI, and Mr Chris Perry for proofreading.

References

- Achard F., Eva H.D., Stibig H., Mayaux P., Gallego J., Richards T. and Malingreau J. 2002. Determination of deforestation rates of the world's humid tropical forests. *Science* 297: 999–1002.
- Akiyama H., Tsuruta H. and Watanabe T. 2000. N₂O and NO emissions from soils after the application of different chemical fertilizers. *Global Change Sci.* 2: 313–320.
- Born M., Dorr H. and Levin I. 1990. Methane consumption in aerated soils of the temperate zone. *Tellus* 42A: 2–8.
- Bouwman A.F., Fung I., Matthews E. and John J. 1993. Global analysis of the potential for N₂O production in natural soils. *Global Biogeochem. Cycles* 7: 557–597.
- Breuer L., Papen H. and Butterbach-Bahl K. 2000. N₂O emission from tropical forest soils of Australia. *J. Geophys. Res.* 105: 26353–26367.
- Cicerone R.J. and Oremland R.S. 1988. Biogeochemical aspects of atmospheric methane. *Global Biogeochem. Cycles* 2: 299–327.
- Davidson E.A., Keller M., Erickson H.E., Verchot L.V. and Veldkamp E. 2000a. Testing a conceptual model of soil emissions of nitrous and nitric oxides. *BioScience* 50: 667–680.
- Davidson E.A., Verchot L.V., Cattaneo J.H., Ackerman I.L. and Carvalho, J.E.M. 2000b. Effects of soil water content on soil respiration in forests and cattle pastures of eastern Amazonia. *Biogeochemistry* 48: 53–69.
- Day P.R. 1965. Particle fractionation and particle-size analysis. In: Black C.A., Evans D.D., Ensminger L.E., White J.L. and Clark F.E. (Eds) *Methods of Soil Analysis Part 1 – Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling*. American Society of Agronomy, Inc., Madison, WI, pp. 545–567.
- Dörr H., Katruff L. and Levin I. 1993. Soil texture parameterization of the methane uptake in aerated soils. *Chemosphere* 26: 697–713.
- Eggleton P., Homathevi R., Jones D.T., MacDonald J.A., Jeeva D., Bignell D.E., Davies R.G. and Maryati M. 1999. Termite assemblages, forest disturbance and greenhouse gas fluxes in Sabah, East Malaysia. *Phil. Trans. Royal Soc. London Ser. B – Biol. Sci.* 354: 1791–1802.
- Hart S.C., Stark J.M., Davidson E.A. and Firestone M.K. 1994. Nitrogen mineralization, immobilization, and nitrification. In: Weaver R.W., Angle J.S. and Bottomley P.S. (Eds) *Methods of Soil Analysis Part 2 – Microbiological and Biochemical Properties*. Soil Science Society of America Inc., Madison, WI, pp. 985–1018.
- Hutchinson G.L. and Livingston G.P. 1993. Use of chamber systems to measure trace gas fluxes. In: Harper L.A. (Ed) *Agricultural Ecosystem Effects on Trace Gases and Global Climate*. Am. Soc. Agron., Madison, WI, pp. 63–78.
- IPCC 1995. Summary for policymakers: radiative forcing of climate. In: Houghton J.T., Meira Filho L.G., Bruce J., Hoesung Lee, Callandar B.A., Haites E., Harris N. and Maskell K. (Eds) *Climate Change 1994 Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios*. Cambridge University Press, Cambridge, MA, pp. 72–126.
- Ishizuka S., Tsuruta H. and Murdiyarso D. 2002. An intensive field study on CO₂, CH₄ and N₂O emissions and soil properties at four land-use types in Sumatra, Indonesia. *Global Biogeochem. Cycles* 16: 1049; doi:10.1029/2001GB001614.
- Ishizuka S., Sakata T., Tanikawa T. and Ishizuka K. 2000. N₂O emission and spatial distribution in a Japanese deciduous forest. *J. Jpn. For. Soc.* 82: 62–71.
- Keller M. and Reiners W.A. 1994. Soil-atmospheric exchange of nitrous oxide, nitric oxide, and methane under secondary succes-

- sion of pasture to forest in the Atlantic lowlands of Costa Rica. *Global Biogeochem. Cycles* 8: 399–409.
- Keller M., Veldkamp E., Weitz A.M. and Reiners W.A. 1993. Effect of pasture age on soil trace-gas emissions from a deforested area of Costa Rica. *Nature* 365: 244–246.
- Keller M., Kaplan W.A., Wofsy S.C. and DaCosta J.M. 1988. Emissions of N₂O from tropical forest soils: response to fertilization with NH₄, NO₃ and PO₄. *J. Geophys. Res.* 93: 1600–1604.
- King G.M. and Schnell S. 1994. Effect of increasing atmospheric methane concentration on ammonium inhibition of soil methane consumption. *Nature* 370: 282–284.
- Livingston G.P., Vitousek P.M. and Matson P.A. 1988. Nitrous oxide flux and nitrogen transformations across a landscape gradient in Amazonia. *J. Geophys. Res.* 93: 1593–1599.
- Matson P.A. and Vitousek P.M. 1987. Cross-system comparisons of soil nitrogen transformations and nitrous oxide flux in tropical forest ecosystems. *Global Biogeochem. Cycles* 1: 163–170.
- Murdiyarso D. and Wasrin U.R. 1995. Estimating land use change and carbon release from tropical forests conversion using remote sensing technique. *J. Biogeograph.* 22: 715–721.
- Olsen S.R. and Sommers L.E. 1982. Phosphorus. In: Page A.L., Miller R.H. and Keeney D.R. (Eds) *Method of Soil Analysis Part 2 – Chemical and Microbiological Properties*, Second Edition. American Society of Agronomy, Inc., Madison, WI, pp. 403–430.
- Potter C.S., Davidson E.A. and Verchot L.V. 1996. Estimation of global biogeochemical controls and seasonality in soil methane consumption. *Chemosphere* 32: 2219–2246.
- Prather M., Ehhalt D., Dentener F., Derwent R., Dlugokencky E., Holland E. et al. 2001. Atmospheric chemistry and greenhouse gases. In: Houghton J.T., Ding Y., Griggs D.J., Noguera M., van der Linden P.J., Dai X., Maskell K. and Johnson C.A. (Eds) *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, pp. 239–287.
- Raich J.W. and Potter C.S. 1995. Global patterns of carbon dioxide emissions from soils. *Global Biogeochem. Cycles* 9: 23–36.
- Raich J.W. and Schlesinger W.H. 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. *Tellus* 44B: 81–99.
- Sakamoto K. and Hayashi A. 1999. A rapid method for determining the microbial biomass-N in soil – Determination of total-N in soil extract by peroxydisulfate oxidation method – *Soil Microorganisms* 53: 57–62.
- Sugimoto A., Inoue T., Kirtibutr N. and Abe T. 1998. Methane oxidation by termite mounds estimated by the carbon isotopic composition of methane. *Global Biogeochem. Cycles* 12: 595–605.
- Vance E.D., Brooks P.C. and Jenkinson D.S. 1987. An extracted method for measuring soil microbial biomass C. *Soil Biol. Biochem.* 19: 703–707.
- Verchot L.V., Davidson E.A., Cattânio J.H. and Ackerman I.L. 2000. Land-use change and biogeochemical controls of methane fluxes in soils of eastern Amazonia. *Ecosystems* 3: 41–56.
- Verchot L.V., Davidson E.A., Cattânio J.H., Ackerman I.L., Erickson H.E. and Keller M. 1999. Land use change and biogeochemical controls of nitrogen oxide emissions from soils in eastern Amazonia. *Global Biogeochem. Cycles* 13: 31–46.