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Spatial patterns of greenhouse gas emission in a tropical rainforest in Indonesia

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Abstract

Spatial patterns of CO_2, CH_4, and N_2O flux were analyzed in the soil of a primary forest in Sumatra, Indonesia. The fluxes were measured at 3-m intervals on a sampling grid of 8 rows by 10 columns, with fluxes found to be below the minimum detection level at 12 points for CH_4 and 29 points for N_2O. All three gas fluxes distributed log-normally. The means and standard deviations of CO_2 and CH_4 fluxes calculated by the maximum likelihood method were 3.68 $\pm$ 1.32 g C m^{-2} d^{-1} and 0.79 $\pm$ 0.60 mg C m^{-2} d^{-1}, respectively. The mean and standard deviation of N_2O fluxes using a maximum likelihood estimator for the censored data set was 2.99 $\pm$ 3.26 μg N m^{-2} h^{-1}. The spatial dependency of CH_4 fluxes was not detected in 3-m intervals, while weak spatial dependency was observed in CO_2 and N_2O fluxes. The coefficients of variation of CH_4 and N_2O were higher than that of CO_2. Some hot spots where high levels of CH_4 and N_2O were generated in the studied field may increase the variability of these gases. The resulting patterns of variability suggest that sampling distances of $>$ 10 m and $>$ 20 m are required to obtain statistically independent samples for CO_2 and N_2O flux in the studied field, respectively. But because of weak or no spatial dependency of each flux, a sampling distance of more than 10 m intervals is enough to prevent a significant problem of autocorrelation for each flux measurement.

Introduction

CO_2, CH_4 and N_2O have been targeted as greenhouse gases (Prather et al. 2001). It is very important to know the precise variation in the intensity of these gas fluxes in tropical regions. Bouwman et al. (1993) estimated the annual global N_2O emission from soils as 6.8 Tg N, 80% of which was derived from the tropics. The global CH_4 uptake rate by soils was estimated as 15 to 35 Tg y^{-1}, and humid tropical forest accounts for 10 to 20% of this (Potter et al. 1996). The annual CO_2 flux from soils to the atmosphere is estimated to be 76.5 Pg C y^{-1} globally (Raich and Potter 1995), and the CO_2 flux from tropical moist forest is the highest of all terrestrial ecosystems (Raich and Potter 1995).

Most ecosystems are spatially heterogeneous, but little attention has focused on quantifying the field scale variability of greenhouse gas emissions, especially in the tropical regions. For quantitative assessment, representative field measurements and information on spatial structure are needed. Geostatistical analysis is useful for examining the structure of the spatial variability (e.g., Oliver and Webster 1991). Geostatistical analysis has been applied in various soil studies, for example, about soil chemical properties (Yost et al. 1982; Paz-González and Taboada 2000), litter components (Gourbiere and Debouzie

1995), soil infiltration rate (Vieira et al. 1981), and enzyme activities (Bergstrom 1998) in order to clarify spatial structure, and various review articles have been published (Parkin 1993; Goovaerts 1998). In the studies of greenhouse gas emissions, clarification of the spatial variability is one of the intensively studied categories, especially for N_2O emissions. N_2O emissions are well known to show high spatial variability in various land-uses (Velthof et al. 1996; Verchot et al. 1999) and many reports have focused on the importance of the location on the slope for N_2O emission and denitrification (Pennock et al. 1992; Reiners et al. 1998; Ishizuka et al. 2000). But there are few reports using geostatistical analysis in order to clarify the spatial structure for N_2O emission (Ambus and Christensen 1994; Velthof et al. 1996; Clemens et al. 1999; Weitz et al. 1999). Probably because of the relatively smaller coefficient of variation of CO_2 flux in the field, less attention has been paid to the spatial structure of CO_2 flux. For this reason there is little information about an adequate sampling distance for CO_2 to minimize autocorrelation (Ambus and Christensen 1994; Rayment and Jarvis 2000). This shortage of information on the spatial structure of CO_2 fluxes is also applicable to that of CH_4 flux, especially in tropical regions where CH_4 flux shows high variability (Verchot et al. 2000) and information on the spatial structure may be more important.

Our objectives are to present preliminary information about the spatial structure of CO_2, CH_4 and N_2O emissions in a 21 by 27 m area in a tropical rain forest in Sumatra, Indonesia by geostatistical analysis and to contribute to the progress of the knowledge on the sampling design of these gas fluxes in such tropical regions.

Material and methods

Sampling site and sampling design

To determine the spatial variation of greenhouse gas emissions from tropical rain forests in Indonesia, we conducted sampling on an 8 × 10 grid in a primary forest on 14 September 2001. The mean annual rainfall was 2400 mm y^{-1} for 1998 through 2001. The mean soil temperature at the depth of 5 cm was 26 ºC in this experimental period. More detailed information on this forest has been described elsewhere (Ishizuka et al. 2002) as the same forest as the plot P1 and P2 in Pasir Mayang Research Site).

A sampling grid was prepared on the studied field, with 8 rows oriented E–W and 10 columns N–S (Figure 1). The interval between sampling points was 3 m. A set of 20 chambers was used for flux measurement. The gas samples for flux measurement were taken first from the westernmost two rows (1 and 2). After sampling from rows 1 and 2, we removed the chambers and set them on rows 3 and 4 and so on until all 80 points were sampled. The fluctuation of soil temperature did not affect the flux measurement in this experimental period, because it was relatively small (the mean and standard deviation of soil temperature at 5 cm depth were 26.0 ± 0.2 ºC and the difference between maximum and minimum temperature was 0.6 ºC). We took three time series (0, 10, 20 min) of gas samples per chamber (0.25 m diameter, 0.15 m height) after covering the chamber with a lid. The gas concentration was determined by two gas chromatographs (Shimazu GC-9A-TCD-FID and Shimazu GC-14B-ECD). The methods of sampling transportation and gas analysis are detailed elsewhere (Ishizuka et al. 2005 (this issue)).

Statistical analysis

For each flux measurement we calculated the minimum significant flux (α=0.10; Hutchinson and Livingston 1993). All flux was significant from zero in the CO_2 flux calculation. The minimum fluxes considered as significant from zero for CH_4 and N_2O were 0.18 mg C m^{-2} d^{-1} and 1.49 μg N m^{-2} h^{-1}, respectively, and we defined the trace data as the flux whose absolute value was below these values. For the CH_4 flux, because the trace data (n=12) were supposed to be distributed evenly between −0.18 and 0.18 mg C m^{-2} d^{-1} and the bias to replace them to zero could be considered negligible for further calculation, the trace data were replaced as zero. For the trace data of N_2O flux, we used two ways for further calculation. One is the calculation of arithmetic mean and standard deviation and geostatistical analysis, in which the trace data were replaced with one half of the detection limit (namely, 0.75 μg N m^{-2} h^{-1}) (Kushner 1976; Gilbert 1987). And the other is the estimation of log-transformed mean and standard deviation of the flux, using the maximum likelihood method for the censored data set (Gilbert 1987; Kuttatharmmakul et al. 2000).

Parkin et al. (1988) suggest that attention should focus on statistics of data whose distribution is log-normal. Because the distribution of the flux data for

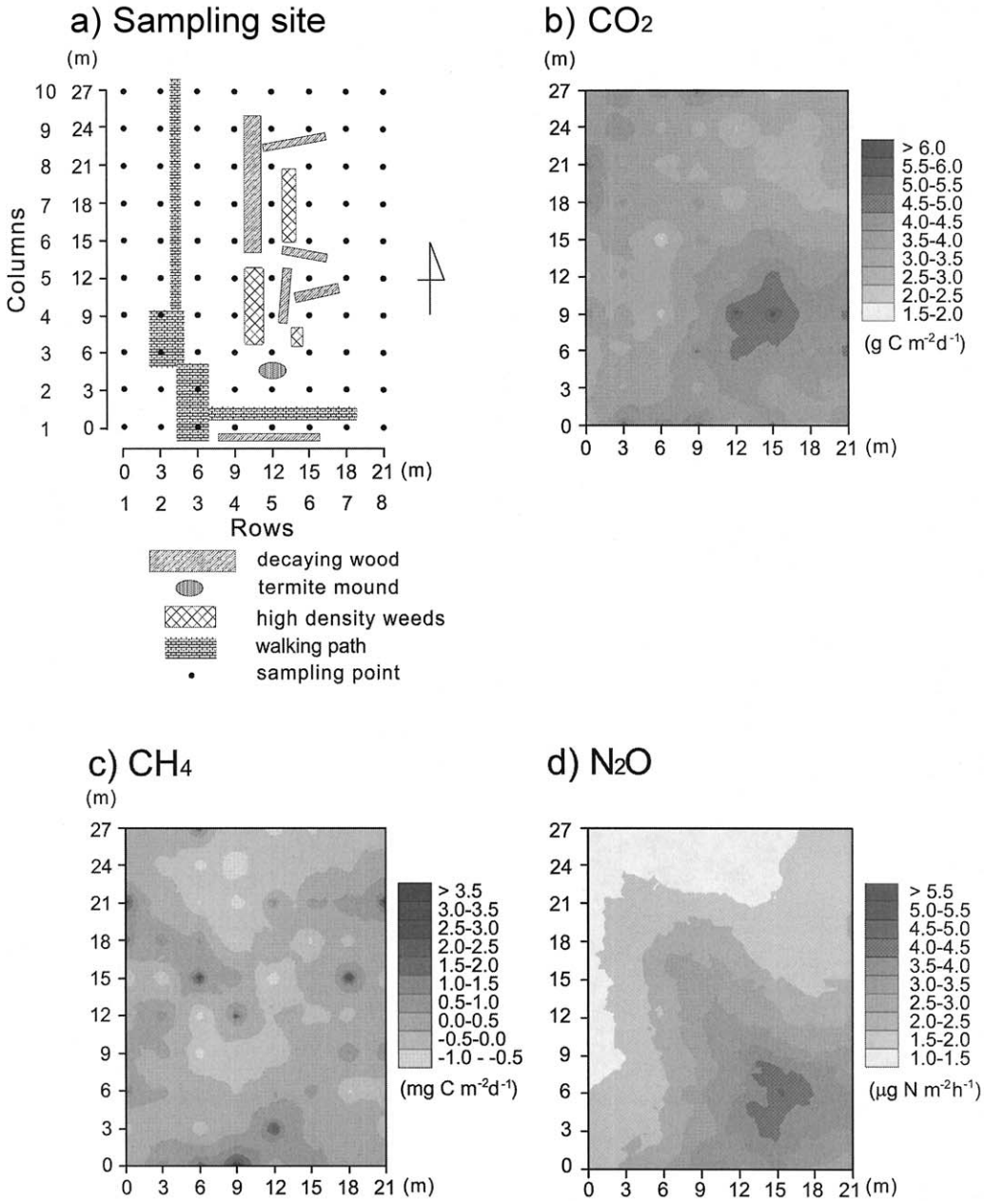

Figure 1. The sampling design and properties of the sampling site (a), and the maps of (b) CO_2, (c) CH_4, and (d) N_2O fluxes within the study area. The maps of CO_2 and CH_4 were created by the inverse distance weighting method. The map of N_2O was created by block kriging with a block size of 0.4 m^2 having a 2 × 2 grid size in the block.

CO_2 and CH_4 obtained in this study was log-normal, we adopted the maximum likelihood method (Parkin et al. 1988) of estimating the mean and coefficient of variation for these gases, in the light of the relatively low skewness of data and sufficiency of data points.

Experimental variograms were used to quantify the spatial dependence of CO_2, CH_4 and N_2O fluxes (GS+ version 5.3b, Gamma Design Software, Michigan, USA). According to the log-normal frequency distributions in these fluxes, flux data for them were log-transformed for geostatistical analysis.

Table 1. The statistical data of CO_2, CH_4 and N_2O emission rates.

Number of observations of trace data		Untransformed							Maximum Likelihood by Log-transformed Data		
		Mean	Median	SD	Min.	Max.	Skewness	CV (%)	Mean	SD	CV (%)
		($g\ C\ m^{-2}\ d^{-1}$)							($g\ C\ m^{-2}\ d^{-1}$)		
CO_2	0	3.68	3.26	1.32	1.56	7.18	0.79	36	3.68	1.32	36
		($mg\ C\ m^{-2}\ d^{-1}$)							($mg\ C\ m^{-2}\ d^{-1}$)		
CH_4	12	0.83[a]	0[a]	2.18[a]	− 1.34	8.28	1.63[a]	136[a]	0.80[a]	0.61[a]	76[a]
		($\mu g\ N\ m^{-2}\ h^{-1}$)							($\mu g\ N\ m^{-2}\ h^{-1}$)		
N_2O	29	2.84[b]	1.98[b]	2.60[b]	Tr.[c]	11.0[b]	1.53[b]	92[b]	2.99[d]	3.26[d]	109[d]

[a]The trace data were replaced as 0; [b]The trace data were replaced as one half of the detection limit; [c]Trace; [d]Using maximum likelihood estimation from the censored data sets (Gilbert 1987).

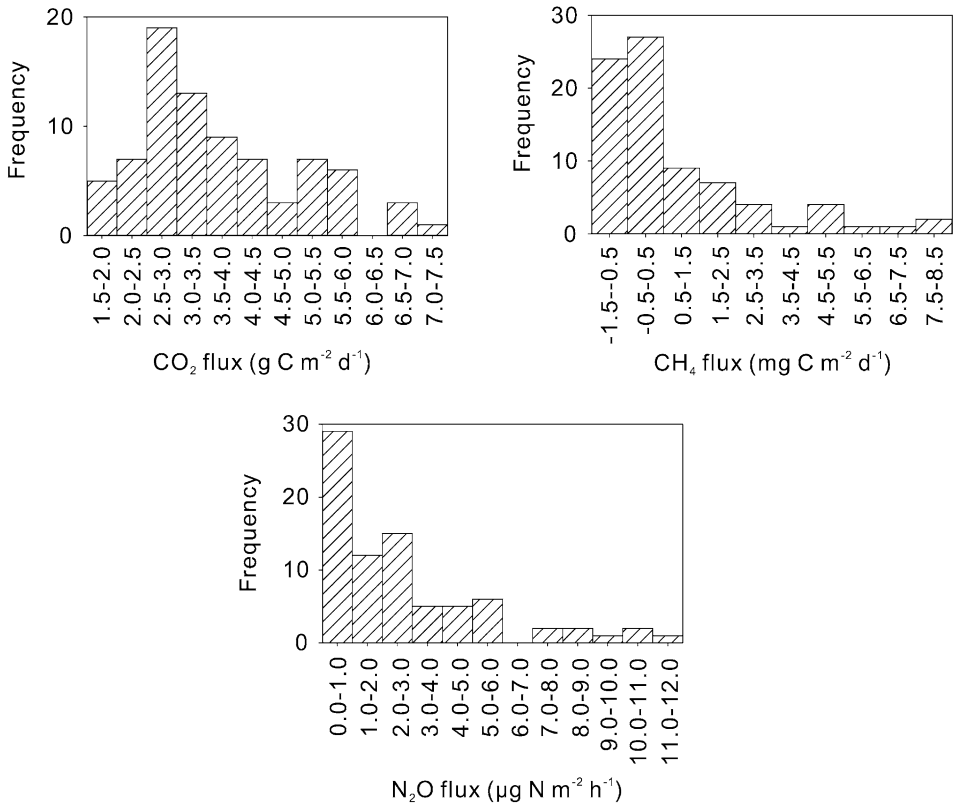

Figure 2. Frequency distribution of CO_2 (upper left), CH_4 (upper right), and N_2O (lower) fluxes.

To analyze the relationship between each of the gas fluxes, we used nonparametric statistics of Spearman rank correlation.

Results and discussion

The results of each flux are summarized in Table 1. All three gas fluxes were log-normally distributed (Figure 2), as indicated by a Q-Q plot of log-transformed and non-transformed fluxes (Figure 3). However, at 12 points of CH_4 flux and 29 points of N_2O flux (15 and 36% of all sampling points, respectively), the flux was under the detection limit (Table 1). The log-normal distribution of N_2O flux contrasts with the results of other reports, suggesting a normal distribution (Clemens et al. 1999), but agrees with the results of still other reports (e.g., Ambus and Chris-

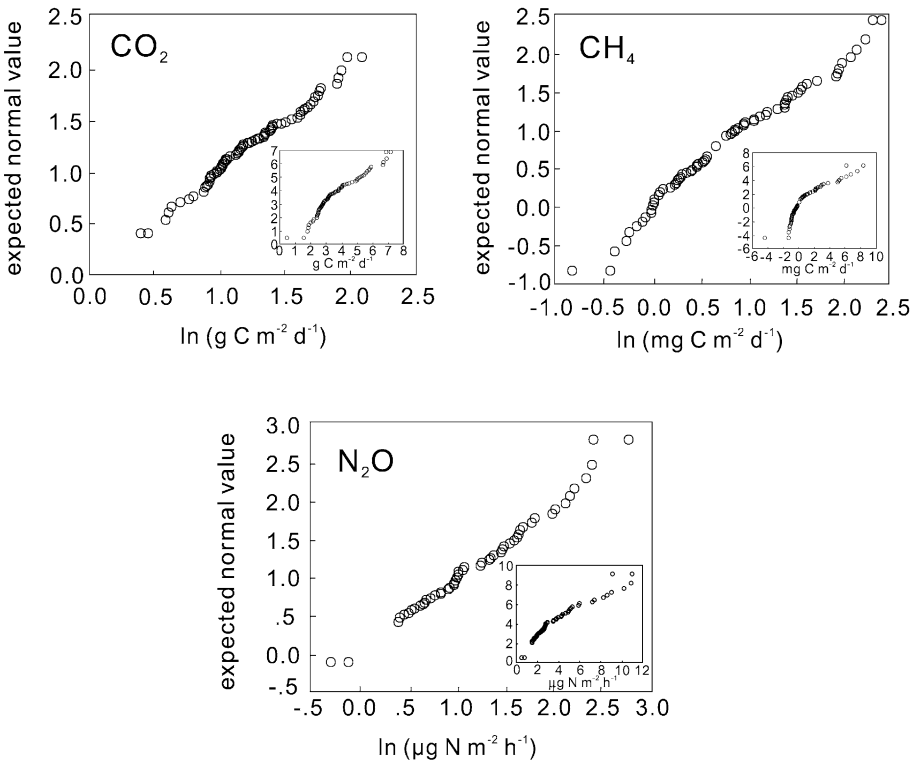

Figure 3. Q-Q plot of log-transformed fluxes: CO_2 (upper left), CH_4 (upper right), and N_2O (lower) fluxes. The inset is a Q-Q plot of non-transformed fluxes.

tensen 1994). The means and standard deviations of CO_2 and CH_4 flux calculated by the maximum likelihood method were 3.68 $\pm$ 1.32 g C m^{-2} d^{-1} and 0.79 $\pm$ 0.60 mg C m^{-2} d^{-1}, respectively. The mean and standard deviation of N_2O was 2.99 $\pm$ 3.26 µg N m^{-2} h^{-1} by the estimation of log-transformed mean and standard deviation of the flux, using the maximum likelihood method for a censored data set. The coefficient of variation for log-transformed values of CH_4 (76%) and N_2O (109%) was higher than that for CO_2 (36%) (Table 1). Between CO_2 and CH_4 flux and between CO_2 and N_2O flux there was a weak positive correlation (Spearman rank correlation, R=0.345 and 0.354, respectively; Table 2).

The variograms of log-transformed CO_2 flux showed weak spatial dependence (Figure 4), and a spherical model was selected according to the minimum residual sums of squares (RSS; 2.026E − 04, R^2=0.623). Few studies have addressed the spatial variability of soil CO_2 efflux (Rayment and Jarvis 2000). The value of the range parameter in this study is relatively greater than in Rayment and Jarvis (2000). The range parameter is 10 m, indicating that to obtain statistically independent samples for CO_2 flux we need a sampling interval of greater than 10 m.

The semivariance of N_2O gradually increased with the increase of the separation distance (Figure 4), fitted by an exponential model with the parameters of sill, range and nugget as 1.62, 195 m and 0.55, respectively (R^2 = 0.842; RSS = 1.97). This pattern of semivariogram was comparable with a previous report of analysis of N_2O fluxes in mown and grazed grassland (Velthof et al. 1996). The range and sill obtained are not precisely determined, because we did not make measurements at distances of more than 27 m. The nugget is equivalent to 1.73 µg N m^{-2} h^{-1}, which is close to the detection limit (1.49 µg N m^{-2} h^{-1}), this result suggesting that the nugget effect is mainly due to measurement error. The range parameter of 195 m is unreliable as mentioned above, but the result suggests that to obtain statistically independent samples for N_2O flux we need a sampling interval of greater than 20 m in this site.

The variograms of log-transformed CH_4 flux show no change of semivariance with distance (Figure 4),

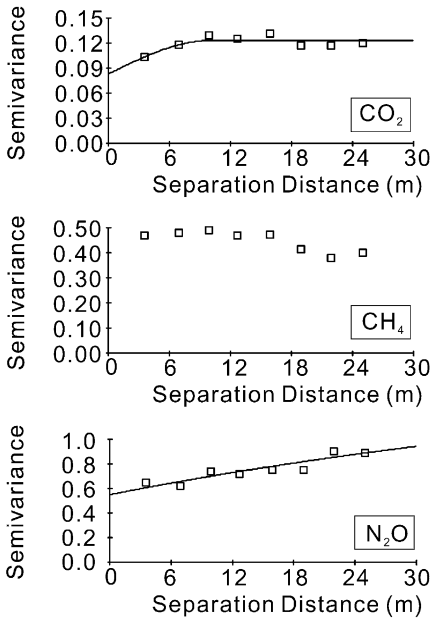

Figure 4. Variograms of log-transformed fluxes of CO_2 (top), CH_4 (middle), and N_2O (bottom). The line in the variograms of CO_2 flux was fitted by a spherical model; the sill, range and nugget are 0.123, 10.0, and 0.083, respectively. The line in the variograms of N_2O flux was fitted by an exponential model; the sill, range and nugget are 1.62, 195 m and 0.55, respectively.

Table 2. Non-parametric correlation coefficient of all gas fluxes.

		CH_4	N_2O
CO_2	R	0.345	0.354
	n	80	51
	p	0.002	0.011
CH_4	R		0.183
	n		51
	p		0.198

indicating that there is no spatial dependence for CH_4 flux over 3-m intervals. The 3-m intervals of grid are too large and the distance showing spatial dependency may be smaller than 3 m. Previous studies suggest that there are 'hot spots' where high levels of N_2O are generated (e.g., Kessel et al. 1993). We also observed relatively high N_2O or CH_4 flux at several points, and the spatial dependence was considered low due to these hot spots.

According to our measurements, for both CH_4 and N_2O emissions, the evaluation of total fluxes is significantly affected by hot spot coverage by the chambers. This hot spot heterogeneity could be greater than the effect of nearby autocorrelation. Because of weak or no spatial dependency of each flux, the sampling distance in more than 10 m intervals is enough to prevent a significant problem of autocorrelation for each flux measurement.

Using the parameter from variogram analysis, a map of N_2O flux was produced by block kriging (Figure 1) and the maps of CO_2 and CH_4 were produced by the inverse distance weighting method. The greatest CO_2 flux concentrated around an area with dense weed (near the point of row 5 to 6, column 4, in Figure 1), suggesting that root respiration of weed is an important source in the studied field. The sampling points that showed high CH_4 flux (> 1.8 mg C m^{-2} d^{-1}) were mainly located along the walking path (Figure 6). The plausible sources for this high CH_4 flux were termites. In this forest the termite population can be high (Ishizuka et al. 2005 (this issue)). Also it is possible that the soil along the walking path was compacted by human activity and its soil gas diffusivity was reduced, limiting the diffusion of oxygen to the deeper soil. As a result of high CH_4 production by anaerobic methanogenesis, production exceeded consumption. Our data do not indicate which idea is more favorable. Further research is needed to clarify the source of CH_4. These results suggest that the spatial patterns of these greenhouse gases are strongly affected by human foot traffic through the site, plants and insects.

Trace gas flux measurements were made only one time. The spatial dependency may fluctuate with the fluctuation of soil properties. Velthof et al. (1996) suggested that the strong temporal variation of flux controlling factors may affect the stability of semivariograms of fluxes, and generally applicable semivariograms cannot be obtained. The sampling period in this research was mid-September, which is the transitional period from dry to wet season. Averaged soil water content in September was 0.11 Mg m^{-3}, which is relatively dry but close to the annual mean of soil water content (0.13 ± 0.03 Mg m^{-3}) in this forest (non-calibrated values, measured by TDR at 7.5 cm depth for two years, unpublished data). It is possible that drastic change of spatial variation could occur after heavy rainfall. We expect, however, that the general picture provided in this spatial study is typical of the site in which the spatial variation of CO_2 flux is smaller than those of CH_4 and N_2O. There is little information about the spatial structure of greenhouse gas emissions in tropical forests and additional studies are needed to produce more general images.

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