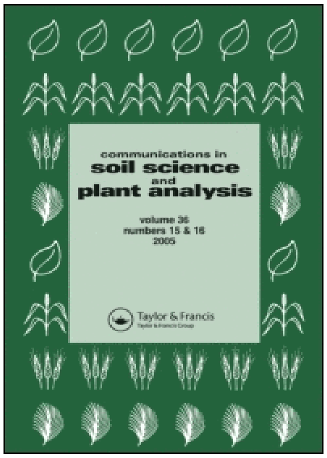

Communications in Soil Science and Plant Analysis

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597241

Daytime, Temporal, and Seasonal Variations of N_2O Emissions in an Upland Cropping System of the Humid Tropics

To link to this article: DOI: 10.1080/00103620601094122
URL: http://dx.doi.org/10.1080/00103620601094122

Communications in Soil Science and Plant Analysis, 38: 189–204, 2007

ISSN 0010-3624 print/1532-2416 online
DOI: 10.1080/00103620601094122

Daytime, Temporal, and Seasonal Variations of N_2O Emissions in an Upland Cropping System of the Humid Tropics

M. I. Khalil
Soil Science Division, Bangladesh Institute of Nuclear Agriculture, Mymensingh, Bangladesh and Institute of Plant Nutrition, Department of Plant Sciences, Technical University Munich, Freising, Germany

O. Van Cleemput
Faculty of Agricultural and Applied Biological Sciences, Ghent University, Ghent, Belgium

A. B. Rosenani
Department of Land Management, University Putra Malaysia, Selangor, Malaysia

U. Schmidhalter
Institute of Plant Nutrition, Department of Plant Sciences, Technical University Munich, Freising, Germany

Abstract: Nitrous oxide (N_2O) contributes to global climate change, and its emission from soil–crop systems depend on soil, environmental, and anthropogenic factors. Thus, we evaluated the variability of N_2O emissions measured by microchambers (cross section: 184 cm^2) from a groundnut–fallow–maize–fallow cropping system of the humid tropics. The crops received inorganic nitrogen (N) plus crop residues (NC), inorganic N alone as ammonium sulfate (RN), and half of the inorganic N along with crop residues and chicken manure ($N_{1/2}CM$), amounting for the crop rotation to 322, 180, and 400 kg N ha^{-1} yr^{-1}, respectively. The N_2O fluxes during the groundnut–maize crop rotation were log-normally distributed, and the frequency

Received 26 April 2005, Accepted 15 March 2006
Address correspondence to M. I. Khalil, Institute of Plant Nutrition, Department of Plant Sciences, Technical University Munich, 85350 Freising-Weihenstephan, Germany. E-mail: khalil_ibrahim@yahoo.com

distributions were positively skewed. Daytime changes in N_2O fluxes were inconsistent, and the 50% of total N_2O emission during the 12 h measurement periods was attained earlier under maize ($\sim$11 : 00 h) than groundnut covers ($\sim$13 : 00 h). Spatial variability in each treatment with eight gas chambers was large but smaller during the cropping periods than the fallow, indicating masking efficiency of crop covers for the soil heterogeneity that was accelerated presumably by antecedent climatic variables. The temporal variability of N_2O emissions was also large (coefficients of variation, CV, ranged from 60 to 81%), involving both input differences between treatments and measurement periods. As such, the relative deviation from the annual mean of total N_2O emission was high during the period after a large N application with a maximum of +480%, due to addition of chicken manure. The seasonal contribution of summer and monsoon to N_2O emissions was insignificant. However, intensive rainfall negatively (-0.65^{**}) and the amount of added N from either source positively (0.83^{***}) correlated with the integrated N_2O emissions, and those were exponential. Results suggest that around noon (12 : 00 h) gas collection could represent well the daily N_2O fluxes, increasing the number or size of the gas chambers could minimize the large variability, and mainly the rainfall and N inputs regulated its emissions in the humid tropics of Malaysia.

Keywords: Climate, humid tropics, N_2O emissions, N sources, variability

INTRODUCTION

Nitrous oxide (N_2O), formed during nitrification and denitrification, causes global warming and stratospheric ozone depletion (Beauchamp 1997). The use of synthetic and organic N fertilizer and biological N fixation in agricultural systems contribute about 60% of the total annual anthropogenic N_2O emission (Mosier et al. 1996). Soil characteristics, amounts of fertilizer, rainfall, and soil temperature could be the main determinants for N_2O emission provided that the other factors are not limiting. This is particularly true for the temperate regions and subtropics, where marked variations of temperature levels exist. In the humid tropics, however, temperature and rainfall are more evenly distributed throughout the year. It is apparent that the climatic conditions of the humid tropics may not be important limiting factors for N_2O production and release.

Microorganisms, through their growth dynamics or enzyme production rates, regulate the spatial variability of N_2O when the other input variables are constant (Müller et al. 1997). A large number of flux chambers and good measurement techniques are required to obtain a high precision of mean N_2O flux (Folorunso and Rolson 1984; Parkin, Sextone, and Tiedje 1987). Diurnal variations of N_2O emission differ particularly with climatic factors. They are closely associated with the variability in topsoil temperature, denitrifying/nitrifying activity, and N_2O diffusion out of the soil profile (Ryden, Lund, and Focht 1978). Temporal changes are significantly influenced by year, crop, and N application, (Flessa, Dörsch, and Beese 1995). The type of N fertilizers affects N_2O emissions during the weeks following fertilizer application, and organic materials with contrasting C/N ratios also affect the formation and release of it (Khalil et al. 2001, 2002a). Different N fertilizers and soil moisture conditions, influenced by rainfall or irrigation, result in a different temporal pattern of N_2O emission (Hénault et al. 1998). These variations are typical for seasonal distribution of N_2O from agricultural land in temperate regions (Christensen 1983; Van Kessel, Pennok, and Farrell 1993; Granli and Bøckman 1994). Information on the spatial distribution and stochastic patterns of its emissions are required in modeling efforts of the atmospheric N_2O concentrations. However, climatic situations of the humid tropics completely differ from temperate regions, importantly influencing temporal and seasonal patterns of N_2O emission, the information on which is scarce. Besides, adequate information on daytime variations of N_2O fluxes is important for a reliable estimate of the natural and fertilizer-induced N_2O emissions. Thus, we compare the spatial variability that occurred at each day of measurements during the cropping and fallow periods with the findings of other works. Besides, we examined the daytime changes of N_2O emissions to identify a representative period for gas collection and the seasonal changes of it with climatic variables and N managements in an upland cropping system of the humid tropics.

MATERIALS AND METHODS

A field experiment was conducted in an experimental farm of the Universiti Putra Malaysia (101° 42′ E, 3° 02′ N). The field had a slope of 9°. The soil was well drained, belonging to the Bungor series (loamy, kaolinitic, isohyperthermic family of Typic Paleudults). The pH_{H2O} was low (5.3), and the organic C content and CEC were 1.25% and 6.86 $Cmol_c\ kg^{-1}$, respectively. Rainfall was more or less well distributed throughout the year with the lowest value in April (24 mm). More than 100 mm was recorded for the rest of the months, with an annual rainfall of 2293 mm. The minimum and maximum air temperature was 19.5 and 34.5°C. The air humidity ranged from 72 to 100% with an average of about 90%.

This study was carried out using a groundnut–maize crop rotation for a 1-yr period. It started with groundnut (day 1–90), followed by a fallow period (day 90–178), a maize-growing period (day 178–285), and again a fallow period (day 285–365). The treatments were recommended inorganic N + crop residues (NC), recommended inorganic N only (RN), and half the dose of the recommended inorganic N + crop residues + chicken manure ($N_{1/2}$CM). The experiment was conducted in a randomized complete block design with four replications for each treatment. The size of each plot was 20 m × 8 m with a total area of 3145 m^2, keeping one plot/block fallow throughout the year. The recommended N dose was 30 $kg\ N\ ha^{-1}$ for groundnut, applied in furrows immediately before sowing of seeds. For maize, $(NH_4)_2SO_4$ at a rate of 150 $kg\ N\ ha^{-1}$ was applied in two splits (2/3 before sowing in furrows and 1/3 at silking stage by single-band placement) as per treatments. All experimental units under each crop received P and K at the same rate (90 kg ha^{-1}) as triple superphosphate and muriate of potash, respectively, during final land preparation. Chicken manure (C/N = 9.6) at a rate of 10 t ha^{-1} (on a wet-weight basis, moisture content 22.2%, 168 kg N ha^{-1}) was applied once before the maize cultivation. The field was limed with ground magnesium limestone (2 t ha^{-1}) before each crop cycle. The maize (4.6 t ha^{-1} on dry-weight basis or 72 kg N ha^{-1}, C/N = 34.4) and groundnut (3.0 t ha^{-1} on dry-weight basis or 70 kg N ha^{-1}, C/N = 19.3) residues were spread on the field after harvest of each crop and incorporated a week before cultivation of the succeeding crop. *Rhizobium* inoculated groundnut (*Arachis hypogaea* L.) and maize (*Zea mays* L.) seeds were sown in furrows after application of the fertilizers. The first fallow period (fallow I) followed the groundnut period, and the second fallow period (fallow II) followed the maize period.

Gas samples were collected using the closed chamber technique (cross section: 184 cm^2, height: 8 cm) that was fitted with a vented perplex lid containing a rubber septum at the center. Two gas chambers were placed in between the plants on the ridge of the furrow as per treatment. Gas samples were taken in the morning (09 : 00–11 : 00 h) at short intervals (2–3 days) following fertilizer application/sowing of both groundnut and maize seeds as well as during the respective fallow periods after incorporation of crop residues and application of chicken manure, and thereafter mostly weekly. After gas sampling, using an airtight syringe through a double-sided needle in 10-mL vacutainers, the base of chambers was kept open until the next collection. Gas samples were collected at 0, 15, and 30 min after closing the chambers. The samples were analyzed within a week by gas chromatography (Model HP 6890, Hewlett-Packard, USA, equipped with a ^{63}Ni electron capture detector). The N_2O flux was calculated using a standard equation (Flessa, Dörsch, and Beese 1998).

A separate study was conducted on the same experimental field during the growth periods of groundnut and maize to measure the daytime changes in N_2O emission so as to find a representative time period of gas collection in the humid tropics. For this, four gas chambers were installed on each treatment plot (RN, NC, and $N_{1/2}$CM) additionally. Fertilizer N as $(NH_4)_2SO_4$ at rates of 50 and 100 kg N ha^{-1} was applied inside the chamber in liquid form (100 mL) during the groundnut and maize growing period, respectively, to promote production and diffusion of N_2O. Gas samples were collected 2 days after addition of the N fertilizer, starting from 08 : 00 to 18 : 00 h at an interval of 2 h and analyzed the next day. Soil and air temperature were also measured during the gas collection period.

Though not designed for, the spatial variability of N_2O fluxes indicated by the coefficients of variation (CV) was calculated using the data measured from the 8 chambers per treatment (2 for each plot, 4 replications) for a total of 24 chambers. This was to compare the reliability of our data based on the number of chambers we used with the findings of other workers. Two chambers per plot were installed on two opposite corners, keeping a distance of 4 m between each chamber. Temporal variability of N_2O emissions was calculated by integrating the area under the period of higher and lower N_2O fluxes as well as on a monthly basis. Seasonal total N_2O emission for different cropping/fallow periods were calculated by integrating the area under the curve of daily N_2O fluxes during the groundnut, fallow after groundnut (fallow I), maize, and fallow after maize periods (fallow II). Data on daily temperature, humidity, and rainfall were collected from the meteorological station of the experimental farm. Simple and multiple linear regression analyses between total N_2O fluxes and temperature/rainfall/added N from either source for the corresponding crops/fallow periods were performed. Statistical analysis was done using the statistical package SAS (SAS 1989). Further details of the N_2O emission patterns during the whole experimental year are given elsewhere (Khalil et al. 2002b).

RESULTS AND DISCUSSION

Daytime Variations of N_2O Emissions

Under groundnut cover, difference of daytime N_2O fluxes between treatments was insignificant mainly because of the high spatial variability, ranging from 26 to 91% (Figure 1a). The figure suggests an increasing trend of N_2O flux untill noon, but no clear daytime variation was observed. However, both air and soil temperature increased with time untill noon and dropped gradually thereafter (Figure 1b). In the maize field, a constant N_2O flux was detected untill 14 : 00 h except in the RN treatment, which received only inorganic N fertilizer during the main experimental period (Figure 2a). No significant difference between treatments was found under maize cover. An increasing trend of N_2O flux at 18 : 00 h under both crop covers indicates an influence of microbial activity with temperature change or the declining soil temperature from the peak levels (34.5 to 32.0°C). The soil temperature reached its maximum somewhat later under maize than groundnut covers (Figure 2b).

In general, the N_2O fluxes decreased slightly at the time of maximum temperature (~35°C) under both crop covers. Under groundnut, N_2O emission increased with increasing soil temperature during morning hours. The morning soil temperature under the maize cover was already higher than under groundnut, demonstrating a constant release of N_2O until noon. The highest fluxes were probably associated with a higher denitrifying activity or with a higher rate of N_2O diffusion out of the soil profile (Ryden, Lund, and Focht 1978). It has been reported that as much as 90% of the diurnal N_2O variability could be attributed to changes in soil temperature (Blackmer, Robins, and Bremner 1982). Christensen (1983) observed that diurnal variations were associated mostly with temperature changes. Other factors such as grass root activity and photosynthesis might also have similar influence. The time of minimum and maximum daily fluxes was not consistent under both crop

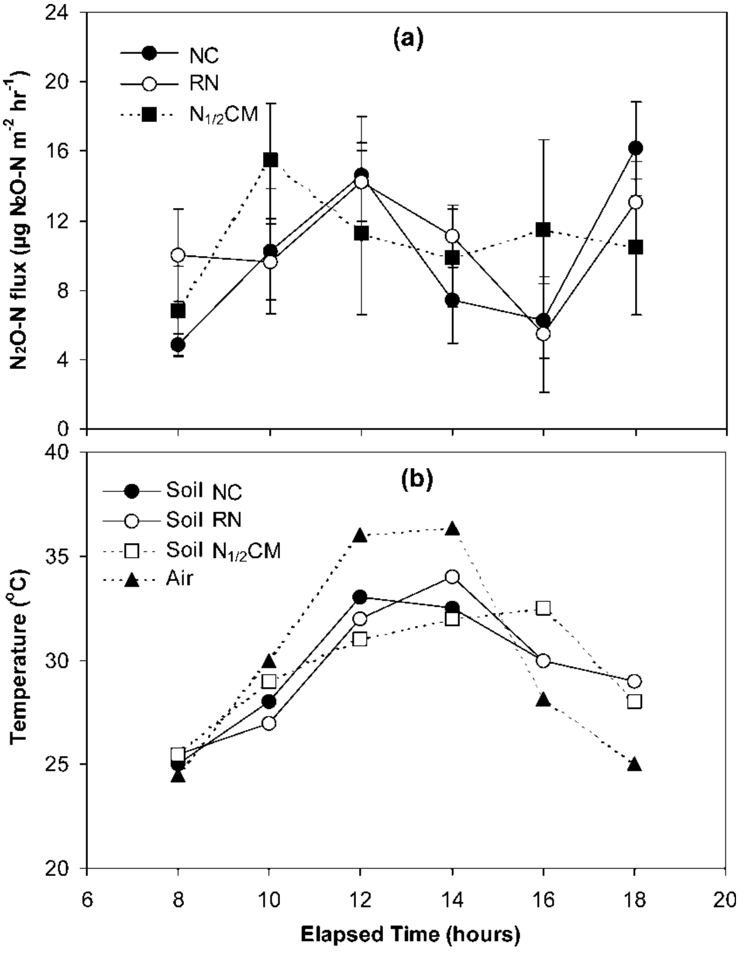

Figure 1. Daytime changes in N_2O fluxes and soil and air temperature measured during the gas collection period in each treatment plot under groundnut cover: (a) N_2O flux and (b) soil and air temperature. NC = recommended N + crop residue; RN = recommended N only; and $N_{1/2}CM = 1/2$ of the recommended N + crop residue + chicken manure. For this study, an additional amount of N at the rate of 50 kg N ha^{-1} was added only in the gas chambers to accelerate N_2O emission. The vertical bars indicate standard errors.

covers. However, 50% of the total N_2O emission was attained between 10 : 00 and 12 : 00 h under maize, and it was between 12 : 00 and 14 : 00 under groundnut covers. This indicates that around noon (averaged ca. 12 : 00 h) gas collection from the upland cropping systems of the humid tropics can be suitable to minimize the daytime variability of N_2O emissions, although other researchers suggested midmorning collection (Ryden, Lund, and Focht 1978).

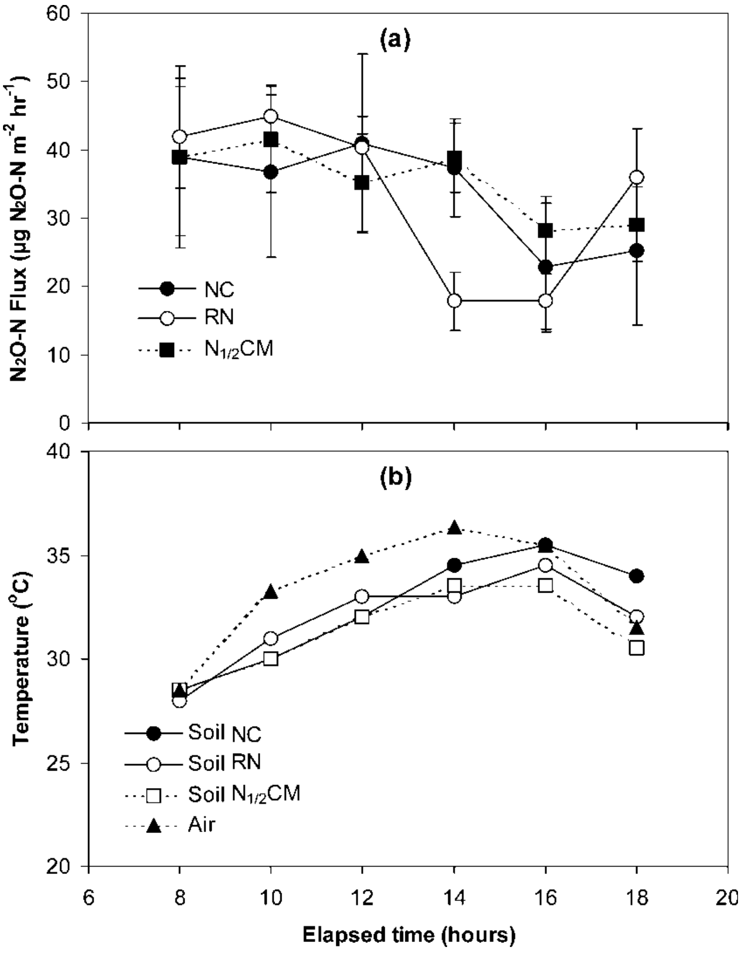

Figure 2. Daytime changes in N_2O fluxes and soil and air temperature measured during the gas collection period in each treatment plot under maize cover: (a) N_2O flux and (b) soil and air temperature. NC = recommended N + crop residue; RN = recommended N only; and $N_{1/2}CM = 1/2$ of the recommended N + crop residue + chicken manure. For this study, an additional amount of N at the rate of 100 kg N ha^{-1} was added only in the gas chambers to accelerate N_2O emission. The vertical bars indicate standard errors.

Ranges and Temporal Variation of N_2O Fluxes

During the 1-yr study, N_2O fluxes from the groundnut–fallow–maize–fallow crop rotation ranged from 34 to 1652 in the NC, −47 to 1358 in the RN, and 51 to 9889 μg N_2O—N m^{-2} d^{-1} in the $N_{1/2}CM$ treatments (Table 1). The median varied from 313 to 748 μg N_2O—N m^{-2} d^{-1}, and the arithmetic means ranged from 426 to 1235 μg N_2O—N m^{-2} d^{-1}, depending on the amount of N added.

The N_2O fluxes were log-normally distributed (Figure 3; estimate values are presented in Table 1). The arithmetic means were higher than the medians in all treatments, indicating that the frequency distributions were positively skewed. The $N_{1/2}CM$ treatment showed a greater skew than the RN and NC treatments. The findings are in agreement with others (Velthof et al. 1996; Yanai et al. 2003). Supply of chicken manure ($N_{1/2}CM$), containing a large amount of N (2.16%), 1 week before sowing of maize dominated the N_2O emission rate (9889 $\mu g\ N_2O$—N $m^{-2}\ d^{-1}$). The high rate of N fertilizer applied into the maize field followed it (4053 $\mu g\ N_2O$—N $m^{-2}\ d^{-1}$), associated with the residual influence of chicken manure. The low N fertilizer rate (30 kg N ha^{-1}) supplied to groundnut as well as the low residual N usually resulted in small N_2O peaks. A maximum flux of it with the NC treatment was found during the fallow period after maize (1265 $\mu g\ N_2O$—N $m^{-2}\ d^{-1}$). The N_2O fluxes corresponded to the differences in applied mineral N. The RN treatment, receiving inorganic N fertilizer only, showed either a low N_2O flux or even a sink.

To comprehend spatial variation of N_2O fluxes with temporal ones, the former was calculated using the eight chambers for each treatment and day of measurements during the cropping (groundnut and maize) and fallow (I and II) periods. The spatial variation was large, and the fallow periods and the maximum coefficients of variation (CV) ranged from 506 to 752% except for fallow II, following maize with the $N_{1/2}CM$ treatment (Table 2). Our CV data were comparatively lower than other findings (up to 6001%) under maize cover (Velthof et al. 1996; Teira-Esmatges, Van Cleemput, and Porta-Casanellas 1998) and fallow periods generally higher, but crop covers (excluding the major peaks in some instances) showed similar CVs to those as observed by other workers (73 to 217%) and showed weak or no spatial dependencies (Yanai et al. 2003; Clemens et al. 1999; Röver et al. 1999; Šimek et al. 2004). The chambers they used were mostly larger than ours, probably largely masking the influence of soil heterogeneity and climatic variability. However, the highest spatial distribution of N_2O fluxes in some instances may be attributed to the differences in N_2O emission and consumption occurring among the chambers of a single treatment and/or large peak differences between gas chambers for a specific treatment, particularly during the fallow periods. Additionally, rainfall/drying events might maintain varied soil moisture and N content between the top and shoulder of the field, having a slope of 9°, leading large differences in N_2O emissions (Yanai et al. 2003; Grant and Pattey 2003). It has been reported that topography also affects hydrology and soil processes, influencing the denitrification rates and N_2O fluxes (Van Kessel, Pennock, and Farrell 1993; Yanai et al. 2003; Grant and Pattey 2003). Indeed, the large variability of N_2O emissions depends on a diverse combination of physical and biological factors of soils rather than on the measurement techniques (Mosier et al. 1996). Though the number of gas chambers we used was within the suggested ranges, results indicate that increasing either the number or the

Table 1. Ranges of N_2O fluxes during the groundnut–fallow–maize–fallow crop rotation as influenced by inorganic and organic N sources

	Quantiles						Moments			Fitted log-normal[a]		
Variables	Maximum	Quartile	Median	Quartile	Minimum	Mean	Standard deviation	Upper/lower 95% mean	Skew-ness/CV	Estimate	Upper 95% mean	Lower 95% mean
NC	1652	784	548	307	34	566	378	688/443	0.90/67	6.1 (0.87)	5.8 (0.74)	6.3 (1.08)
RN	1358	589	313	191	−58	426	349	539/313	1.09/82	5.8 (0.95)	5.5 (0.80)	6.1 (1.18)
$N_{1/2}CM$	9889	1247	748	439	51	1235	1711	1790/681	3.79/139	6.6 (0.97)	6.23 (0.82)	6.9 (1.20)

[a]Values in parentheses are sigma.

Notes: NC = recommended N + crop residue; RC = recommended N only; $N_{1/2}CM$ = 1/2 of the recommended N + crop residue + chicken manure; number of population = 39.

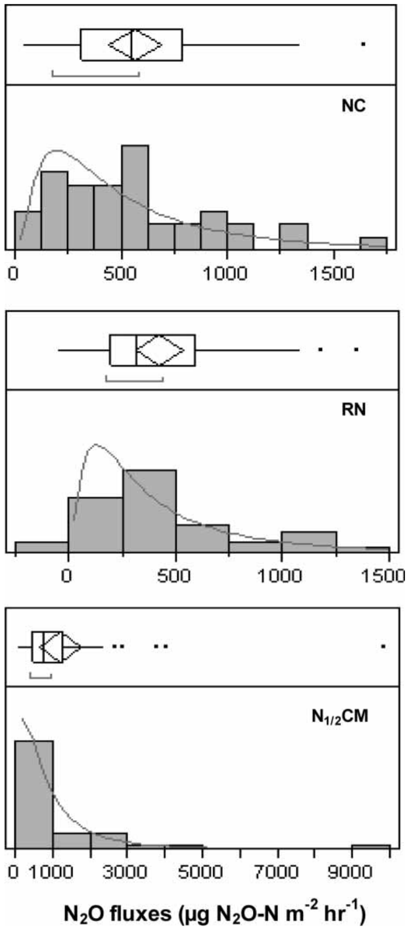

Figure 3. Normal (histograms) and log-normal (lines) distributors of N_2O fluxes measured during the groundnut–fallow–maize–fallow crop rotation as influenced by inorganic and organic N sources. NC = recommended N + crop residue; RC = recommended N only; and $N_{1/2}CM = 1/2$ of the recommended N + crop residue + chicken manure; number of population = 39.

area of chambers could further minimize the large spatial variability of N_2O emissions occurring particularly during the fallow periods; a further study dealing with this will be useful.

A high temporal variation of N_2O fluxes during the 1-yr study was observed and this pattern was mostly pronounced upon application of chicken manure plus a high rate of inorganic N and crop residue. The CV was 60, 81, and 86% for NC, RN and $N_{1/2}CM$, respectively. This is in accordance with the findings of many researchers (Flessa, Dörsch, and Beese 1995;

Table 2. Spatial variations of N_2O fluxes at each day of measurements during the groundnut–maize crop rotation as influenced by inorganic and organic N sources

	Coefficients of variation (%) range		
Cropping/fallow periods	NC	RN	$N_{1/2}CM$
Groundnut	22–84	24–84	38–83
Fallow-I	38–752	29–560	25–506
Maize	37–125	57–216	27–110
Fallow-II	47–645	87–647	40–111

Notes: NC = recommended N + crop residue; RN = recommended N only; and $N_{1/2}CM$ = 1/2 of the recommended N + crop residue + chicken manure.

Kaiser et al. 1998; Kammann et al. 1998). They found even a higher temporal variation with CV values ranging between 100 and 350, 143 and 233, and 136 and 192%, respectively. The temporal variation of N_2O emissions was significantly influenced by both treatments and period of the year ($P < 0.0001$) with an overall CV of 43%. The analysis of variance with monthly integrated N_2O emission, as a single factor considering each treatment separately, showed significant ($P < 0.0001$) differences in N_2O emissions among months of the year, with CVs ranging between 31 and 49%. This is in agreement with other workers (Kaiser et al. 1998).

The observed temporal variation of N_2O fluxes are also in agreement with the relative deviation of monthly integrated emission from the annual mean. The relative deviation from the annual mean (RDAM) was +480% in May with the added chicken manure (Figure 4). Thus, the time pattern of N_2O emissions may be characterized by a short period of its rapid release (Flessa et al. 1998). The RDAM values were less than the annual mean for the months January to April as well as November to December, ranging from −27 to −89%. It indicates the smaller impact of N fertilizer at the low rate applied into groundnut, and the subsequent application of groundnut residue during the fallow period. However, the WFPS (mostly more than 60%) was conducive to release N_2O because of the high rainfall events, except in April (data not shown). The RDAMs from June to October (+6 to +327%) demonstrated the influence of crop residues, high rate of N fertilizer, previously applied chicken manure, and residual N on N_2O emissions. Hence, the magnitude of N_2O release varied between treatments but all treatments exhibited a similar temporal pattern following rainfall events (Burton et al. 1997). Indeed, soil water content before and after the rainfall presumably influenced the air-filled porosities and consequently influenced the temporal changes in denitrification rate in the soil profile (Luo et al. 1998) and N_2O diffusion out of the soil. An important regulatory effect of mineral N or NO_3^- along with soil moisture, which is influenced by rainfall and fertilizer

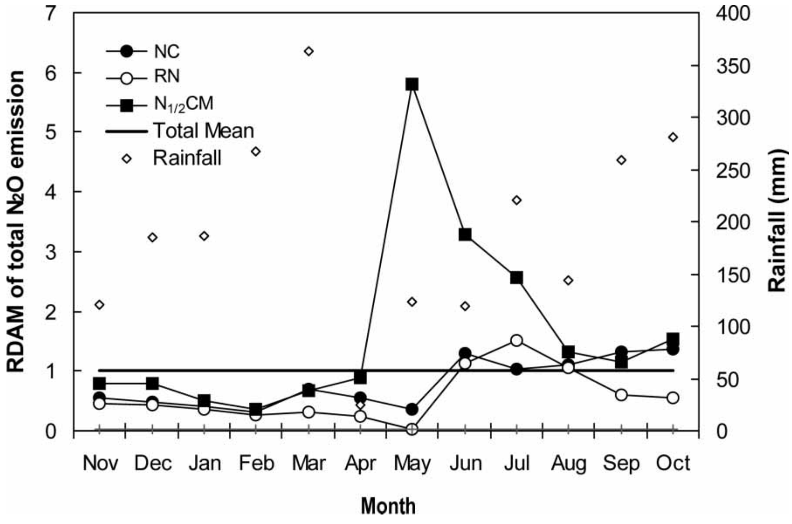

Figure 4. Relative deviation from the annual mean (RDAM) of the total N_2O emission (solid line) as affected by inorganic and organic N sources during the groundnut–maize crop rotation and monthly rainfall. NC = recommended N + crop residue; RN = recommended N only; and $N_{1/2}CM = 1/2$ of the recommended N + crop residue + chicken manure.

N application, has also been emphasized (Hénault et al. 1998; Khalil et al. 2002b). Results indicate that the temporal pattern of N_2O release from the soil system depended more on the availability of N inputs and rainfall events, linking to the N_2O formation processes and its release.

Seasonal Variation of N_2O Emissions

In Malaysia, the difference in terms of temperature and rainfall between summer and monsoon is insignificant, which is typical for the humid tropics. Agricultural practices for crop production could be the major factors affecting the variations of N_2O fluxes. Hence, the seasons were not defined by climatic conditions but rather by crop growth and fallow periods. These were groundnut (90 days), fallow (88 days), maize (107 days), and fallow (80 days) periods. A significant influence of the cropping seasons ($P < 0.001$), treatments ($P < 0.01$), and their interaction ($P < 0.001$) on the variability of total N_2O fluxes was found with a CV of 64%. Irrespective of the treatments, the CVs for the groundnut, fallow I, maize and fallow II periods were 22, 35, 79, and 41%. These indicate that the variation of N_2O emissions was related to the applied inputs and climatic factors to some extent. To confirm this finding, a linear interpolation among temperature, rainfall, and total N_2O was performed. The cumulative temperature in degree-day (°day) values was calculated separately for the groundnut, fallow I, maize, and fallow II periods. They did not show any significant relation with the corresponding total N_2O fluxes (Figure 5a). Indeed, the calculated °day depended on the duration of the crop/fallow periods rather than on the actual temperature variation, of which the difference was small.

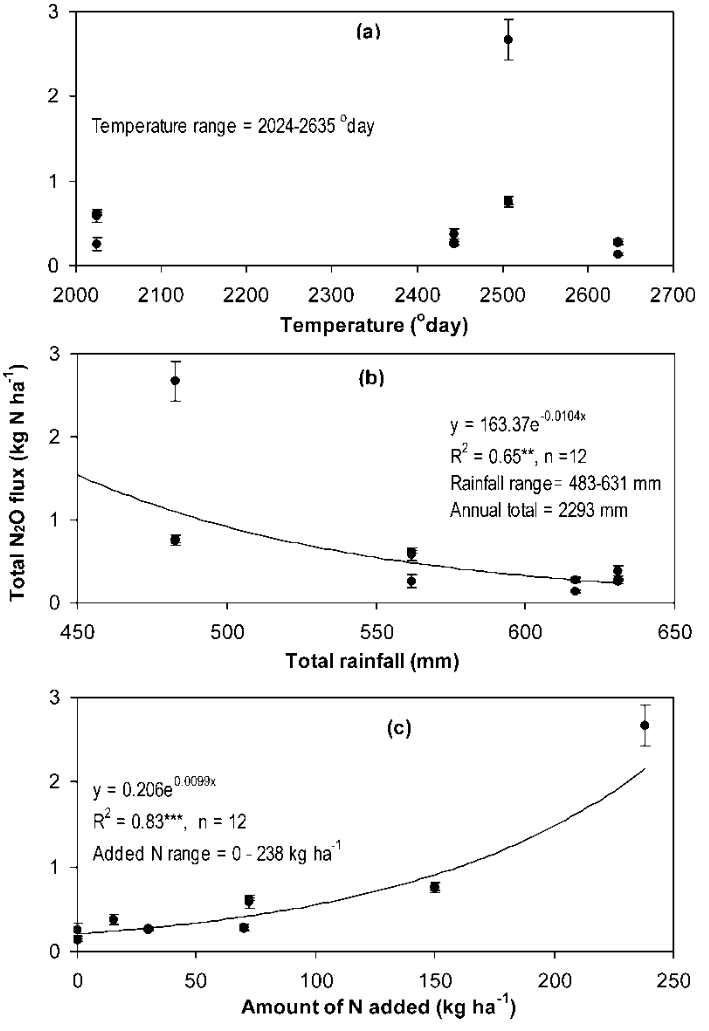

Figure 5. Relations of air temperature (a), rainfall (b), and amounts of applied N with the monthly-integrated N_2O emitted during the groundnut–fallow–maize–fallow periods as influenced by inorganic and organic N sources. The vertical bars indicate standard errors.

The total rainfall during the crop/fallow periods displayed an exponential effect on the N_2O release (Figure 5b). However, the difference in total emission at the lower level of rainfall coincided well with the high N rate, resulting in a large N_2O release. A general but small trend of decreasing N_2O emission at higher rainfall probably exacerbated denitrification activities with more N_2 production or N leaching under intensive and frequent rain events (Hénault et al. 1998; Luo et al. 1998). Figure 5c clearly shows an exponential relation between total N_2O emissions and amount of applied N with a confidence level of 83%. This indicates that the magnitude of high emissions during both crop growth and fallow periods was mostly governed by the availability of mineral N under favorable WFPS (Khalil et al. 2002b; Chang, Cho, and Janzen 1998; Lemke, Izaurralde, and Nyborg 1998). As such, temperature as parameter for seasonal variation demonstrated less effect on N_2O production and release under the humid tropical conditions than rainfall did.

CONCLUSIONS

Results reveal that collection of gas samples around noon from upland cropping systems could be better representative of daytime N_2O emissions, which is usually followed unless automated measurement systems are established. Though the spatial variability of N_2O emissions for each day of measurements was high, they were within the acceptable ranges except some isolated instances measured during the fallow periods. Increasing the number or size of gas chambers could minimize the variability further, which is particularly applicable for the fallow period measurements when the influence of climatic factors could be large. Seasonal response to N_2O emission in terms of summer or monsoon was insignificant because of the relatively even distribution of temperature and rainfall. The rainfall and added N sources largely regulated the temporal or seasonal changes in N_2O evolution. As such, seasonal variations of N_2O fluxes could mostly be explained by the availability of substrates and antecedent rainfall events in the humid tropics.

REFERENCES

Beauchamp, E.G. (1997) Nitrous oxide emission from agricultural soils. *Canadian J. Soil Sci*, 77: 113–123.

Blackmer, A.M., Robins, S.G., and Bremner, J.M. (1982) Diurnal variability in rate of emission of nitrous oxide from soils. *Soil Sci. Soc. Am. J*, 46: 937–942.

Burton, D.L., Bergstrom, D.W., Covert, J.A., Wagner-Riddle, C., and Beauchamp, E.G. (1997) Three methods to estimate N_2O fluxes as impacted by agricultural management. *Canadian J. Soil Sci*, 77: 125–134.

Chang, C., Cho, C.M., and Janzen, H.H. (1998) Nitrous oxide emission from long-term manured soils. *Soil Sci. Soc. Am. J*, 62: 677–682.

Christensen, S. (1983) Nitrous oxide emission from a soil under permanent grass: Seasonal and diurnal fluctuations as influenced by manuring and fertilization. *Soil Biol. Biochem*, 15: 531–536.

Clemens, J., Schillinger, M.P., Goldbach, H., and Huwe, B. (1999) Spatial variability of N_2O emissions and soil parameters of an arable silt loam: A field study. *Biol Fertil. Soils*, 28: 403–406.

Flessa, H., Dörsch, P., and Beese, F. (1995) Seasonal variation of N_2O and CH_4 fluxes in differently managed arable soils in southern Germany. *J. Geophys. Res*, 100: 23115–23124.

Flessa, H., Wild, U., Klemisch, M., and Pfadenhauer, J. (1998) Nitrous oxide and methane fluxes from organic soils under agriculture. *European J. Soil Sci*, 49: 327–335.

Folorunso, O.A. and Rolston, D.E. (1984) Spatial variability of field-measured denitrification gas fluxes. *Soil Sci. Soc. Am. J*, 48: 1214–1219.

Granli, T. and Bøckman, O.C. (1994) Nitrous oxide from agriculture. *Norwegian J. Agric*, 12: 7–128.

Grant, R.F. and Pattey, E. (2003) Modelling variability in N_2O emissions from fertilized agricultural fields. *Soil Biol. Biochem*, 35: 225–243.

Hénault, C., Devis, X., Lucas, J.L., and Germon, J.C. (1998) Influence of different agricultural practices (type of crop, form of N-fertilizer) on soil nitrous oxide emissions. *Biol. Fertil. Soils*, 27: 299–306.

Kaiser, E.-A., Kohrs, K., Kücke, M., Schnug, E., Heinemeyer, O., and Munch, J.C. (1998) Nitrous oxide release from arable soil: Importance of N-fertilization, crops and temporal variation. *Soil Biol. Biochem*, 30: 1553–1563.

Kammann, C., Grunhage, L., Müller, C., Jacobi, S., and Jager, H.-J. (1998) Seasonal variations and mitigations for N_2O emissions from differently managed grasslands. *Environ. Poll*, 102: 179–186.

Khalil, M.I., Boeckx, P., Rosenani, A.B., and Van Cleemput, O. (2001) Nitrogen transformations and emission of greenhouse gases from three acid soils of humid tropics amended with N sources and moisture regimes, II: N_2O and CH_4 fluxes. *Commun. Soil Sci. Plant Anal*, 32: 2909–2924.

Khalil, M.I., Rosenani, A.B., Van Cleemput, O., Shamshuddin, J., and Fauziah, C.I. (2002a) Nitrous oxide production from an Ultisol treated with different nitrogen sources and moisture regimes. *Biol. Fertil. Soils*, 36: 59–65.

Khalil, M.I., Rosenani, A.B., Van Cleemput, O., Fauziah, C.I., and Shamshuddin, J. (2002b) Nitrous oxide emission from a maize–groundnut crop rotation supplied with different nitrogen sources in the humid tropics. *J. Environ. Qual*, 31: 1071–1078.

Lemke, R.L., Izaurralde, R.C., and Nyborg, M. (1998) Seasonal distribution of nitrous oxide emissions from soils in the Parkland region. *Soil Sci. Soc. Am. J*, 62: 1320–1326.

Luo, J., Tillman, R.W., White, R.E., and Ball, P.R. (1998) Variation in denitrification activity with soil depth under pasture. *Soil Biol. Biochem*, 30: 897–903.

Mosier, A.R., Duxbury, J.M., Freney, J.R., Heinemeyer, O., and Minami, K. (1996) Nitrous oxide emissions from agricultural fields: Assessment, measurement and mitigation. *Plant Soil*, 181: 95–108.

Müller, C., Barraclough, D., Ottow, J.C.G., and Jäger, H.-J. (1997) Processes leading to nitrous oxide production in a grassland soil after N fertilization. In *Fertilization for Sustainable Plant Production and Soil Fertility*; Congress Guide and Abstracts of the 11th World Fertilizer Congress, p. 41.

Parkin, T.B., Sextone, A.J., and Tiedje, J.M. (1987) Comparison of field denitrification rates determined by acetylene-based soil core and nitrogen-15 methods. *Soil Sci. Soc. Am. J*, 49: 94–99.

Röver, M., Heinemeyer, O., Munch, J.C., and Kaiser, E.-A. (1999) Spatial heterogeneity within the plough layer: Low and moderate variability of soil properties. *Soil Biol. Biochem*, 31: 175–187.

Ryden, J.C., Lund, L.J., and Focht, D.D. (1978) Direct in-field measurement of nitrous oxide flux from soil. *Soil Sci. Soc. Am. J*, 25: 1527–1536.

SAS. (1989) *SAS Systems Windows, Software Release 6.12 ST020*; SAS Institute, Inc.: Cary, N.C.

Šimek, M., Elhottova, D., Klime, F., and Hopkins, D.W. (2004) Emissions of N_2O and CO_2, denitrification measurements and soil properties in red clover and ryegrass stands. *Soil Biol. Biochem*, 36: 9–21.

Teira-Esmatges, M.R., Van Cleemput, O., and Porta-Casanellas, J. (1998) Fluxes of nitrous oxide and molecular nitrogen from irrigated soils of Catalonia (Spain). *J. Environ. Qual*, 27: 687–697.

Van Kessel, C., Pennock, D.J., and Farrell, R.E. (1993) Seasonal variations in denitrification and nitrous oxide evolution at the landscape scale. *Soil Sci. Soc. Am. J*, 57: 988–995.

Velthof, G.L., Jarvis, S.C., Stein, A., Allen, A.G., and Oenema, O. (1996) Spatial variability of nitrous oxide fluxes in mown and grazed grasslands on a poorly drained clay soil. *Soil Biol. Biochem*, 28: 215–1225.

Yanai, J., Sawamoto, T., Oe, T., Kusa, K., Yamakawa, K., Sakamoto, K., Naganawa, T., Inubushi, K., Hatano, R., and Kosaki, K. (2003) Spatial variability of nitrous oxide emissions and their soil related determining factors in an agricultural field. *J. Environ. Qual*, 32: 1965–1977.