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Daytime, Temporal, and Seasonal Variations of N$_2$O Emissions in an Upland Cropping System of the Humid Tropics

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Abstract: Nitrous oxide (N$_2$O) 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$_2$O 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$_2$O fluxes during the groundnut–maize crop rotation were log-normally distributed, and the frequency...
distributions were positively skewed. Daytime changes in N\textsubscript{2}O fluxes were inconsistent, and the 50\% of total N\textsubscript{2}O emission during the 12 h measurement periods was attained earlier under maize (~11:00 h) than groundnut covers (~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\textsubscript{2}O 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\textsubscript{2}O 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\textsubscript{2}O 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\textsubscript{2}O emissions, and those were exponential. Results suggest that around noon (12:00 h) gas collection could represent well the daily N\textsubscript{2}O 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\textsubscript{2}O emissions, N sources, variability

**INTRODUCTION**

Nitrous oxide (N\textsubscript{2}O), 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\textsubscript{2}O emission (Mosier et al. 1996). Soil characteristics, amounts of fertilizer, rainfall, and soil temperature could be the main determinants for N\textsubscript{2}O 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\textsubscript{2}O production and release.

Microorganisms, through their growth dynamics or enzyme production rates, regulate the spatial variability of N\textsubscript{2}O 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\textsubscript{2}O flux (Folorusso and Rolson 1984; Parkin, Sextone, and Tiedje 1987). Diurnal variations of N\textsubscript{2}O emission differ particularly with climatic factors. They are closely associated with the variability in topsoil temperature, denitrifying/nitrifying activity, and N\textsubscript{2}O 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\textsubscript{2}O 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$_2$O emission (Hénault et al. 1998). These variations are typical for seasonal distribution of N$_2$O 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$_2$O concentrations. However, climatic situations of the humid tropics completely differ from temperate regions, importantly influencing temporal and seasonal patterns of N$_2$O emission, the information on which is scarce. Besides, adequate information on daytime variations of N$_2$O fluxes is important for a reliable estimate of the natural and fertilizer-induced N$_2$O 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$_2$O 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$_{H_2O}$ 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$_4$)$_2$SO$_4$ 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 63Ni electron capture detector). The N\(_2\)O 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\(_2\)O 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\(_4\))\(_2\)SO\(_4\) 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\(_2\)O. 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\(_2\)O 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$_2$O emissions was calculated by integrating the area under the period of higher and lower N$_2$O fluxes as well as on a monthly basis. Seasonal total N$_2$O emission for different cropping/fallow periods were calculated by integrating the area under the curve of daily N$_2$O 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$_2$O 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$_2$O emission patterns during the whole experimental year are given elsewhere (Khalil et al. 2002b).

RESULTS AND DISCUSSION

Daytime Variations of N$_2$O Emissions

Under groundnut cover, difference of daytime N$_2$O 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$_2$O flux until noon, but no clear daytime variation was observed. However, both air and soil temperature increased with time until noon and dropped gradually thereafter (Figure 1b). In the maize field, a constant N$_2$O flux was detected until 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$_2$O 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$_2$O fluxes decreased slightly at the time of maximum temperature (~35°C) under both crop covers. Under groundnut, N$_2$O 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$_2$O until noon. The highest fluxes were probably associated with a higher denitrifying activity or with a higher rate of N$_2$O diffusion out of the soil profile (Ryden, Lund, and Focht 1978). It has been reported that as much as 90% of the diurnal N$_2$O 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
covers. However, 50% of the total N₂O emission was attained between 10:00 and 12:00 h under maize, and it was between 12:00 and 14:00 h 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 N₂O emissions, although other researchers suggested midmorning collection (Ryden, Lund, and Focht 1978).

Figure 1. Daytime changes in N₂O fluxes and soil and air temperature measured during the gas collection period in each treatment plot under groundnut cover: (a) N₂O flux and (b) soil and air temperature. NC = recommended N + crop residue; RN = recommended N only; and N₁/₂CM = 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 N₂O emission. The vertical bars indicate standard errors.
Ranges and Temporal Variation of N$_2$O Fluxes

During the 1-yr study, N$_2$O fluxes from the groundnut–fallow–maize–fallow crop rotation ranged from 34 to 1652 in the NC, 247 to 1358 in the RN, and 51 to 9889 m$^2$N m$^{-2}$d$^{-1}$ in the N$_{1/2}$CM treatments (Table 1). The median varied from 313 to 748 m$^2$N m$^{-2}$d$^{-1}$, and the arithmetic means ranged from 426 to 1235 m$^2$N m$^{-2}$d$^{-1}$, depending on the amount of N added.

Figure 2. Daytime changes in N$_2$O fluxes and soil and air temperature measured during the gas collection period in each treatment plot under maize cover: (a) N$_2$O 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$_2$O emission. The vertical bars indicate standard errors.
The N\textsubscript{2}O 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\textsubscript{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\textsubscript{1/2}CM), containing a large amount of N (2.16%), 1 week before sowing of maize dominated the N\textsubscript{2}O emission rate (9889 μg N\textsubscript{2}O–N m\textsuperscript{-2} d\textsuperscript{-1}). The high rate of N fertilizer applied into the maize field followed it (4053 μg N\textsubscript{2}O–N m\textsuperscript{-2} d\textsuperscript{-1}), associated with the residual influence of chicken manure. The low N fertilizer rate (30 kg N ha\textsuperscript{-1}) supplied to groundnut as well as the low residual N usually resulted in small N\textsubscript{2}O peaks. A maximum flux of it with the NC treatment was found during the fallow period after maize (1265 μg N\textsubscript{2}O–N m\textsuperscript{-2} d\textsuperscript{-1}).

The N\textsubscript{2}O fluxes corresponded to the differences in applied mineral N. The RN treatment, receiving inorganic N fertilizer only, showed either a low N\textsubscript{2}O flux or even a sink.

To comprehend spatial variation of N\textsubscript{2}O 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\textsubscript{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\textsubscript{2}O fluxes in some instances may be attributed to the differences in N\textsubscript{2}O 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\textdegree, leading large differences in N\textsubscript{2}O 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\textsubscript{2}O fluxes (Van Kessel, Pennock, and Farrell 1993; Yanai et al. 2003; Grant and Pattey 2003). Indeed, the large variability of N\textsubscript{2}O 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 N2O fluxes during the groundnut–fallow–maize–fallow crop rotation as influenced by inorganic and organic N sources

<table>
<thead>
<tr>
<th>Variables</th>
<th>Maximum</th>
<th>Quartile</th>
<th>Median</th>
<th>Quartile</th>
<th>Minimum</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>Upper/95% mean</th>
<th>Lower/95% mean</th>
<th>Skewness/CV</th>
<th>Estimate</th>
<th>Upper/95% mean</th>
<th>Lower/95% mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>1652</td>
<td>784</td>
<td>548</td>
<td>307</td>
<td>34</td>
<td>566</td>
<td>378</td>
<td>688/443</td>
<td>0.90/67</td>
<td>5.8 (0.74)</td>
<td>6.1 (0.87)</td>
<td>5.8 (0.74)</td>
<td>6.3 (1.08)</td>
</tr>
<tr>
<td>RN</td>
<td>1358</td>
<td>589</td>
<td>313</td>
<td>191</td>
<td>−58</td>
<td>426</td>
<td>349</td>
<td>539/313</td>
<td>1.09/82</td>
<td>5.5 (0.80)</td>
<td>5.8 (0.95)</td>
<td>5.5 (0.80)</td>
<td>6.1 (1.18)</td>
</tr>
<tr>
<td>N1/2CM</td>
<td>9889</td>
<td>1247</td>
<td>748</td>
<td>439</td>
<td>51</td>
<td>1235</td>
<td>1711</td>
<td>1790/681</td>
<td>3.79/139</td>
<td>6.6 (0.97)</td>
<td>6.23 (0.82)</td>
<td>6.9 (1.20)</td>
<td>6.1 (1.20)</td>
</tr>
</tbody>
</table>

Values in parentheses are sigma.

Notes: NC = recommended N + crop residue; RC = recommended N only; N1/2CM = 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$_2$O emissions occurring particularly during the fallow periods; a further study dealing with this will be useful.

A high temporal variation of N$_2$O 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;
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 N2O 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 N2O emission, as a single factor considering each treatment separately, showed significant ($P < 0.0001$) differences in N2O 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 N2O 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 N2O 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 N2O 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 N2O emissions. Hence, the magnitude of N2O 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 N2O diffusion out of the soil. An important regulatory effect of mineral N or NO3$^-$ along with soil moisture, which is influenced by rainfall and fertilizer

### Table 2. Spatial variations of N2O fluxes at each day of measurements during the groundnut–maize crop rotation as influenced by inorganic and organic N sources

<table>
<thead>
<tr>
<th>Cropping/fallow periods</th>
<th>NC (%)</th>
<th>RN (%)</th>
<th>N$_{1/2}$CM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundnut</td>
<td>22–84</td>
<td>24–84</td>
<td>38–83</td>
</tr>
<tr>
<td>Fallow-I</td>
<td>38–752</td>
<td>29–560</td>
<td>25–506</td>
</tr>
<tr>
<td>Maize</td>
<td>37–125</td>
<td>57–216</td>
<td>27–110</td>
</tr>
<tr>
<td>Fallow-II</td>
<td>47–645</td>
<td>87–647</td>
<td>40–111</td>
</tr>
</tbody>
</table>

**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.
N application, has also been emphasized (Hénault et al. 1998; Khalil et al. 2002b). Results indicate that the temporal pattern of N\textsubscript{2}O release from the soil system depended more on the availability of N inputs and rainfall events, linking to the N\textsubscript{2}O formation processes and its release.

Seasonal Variation of N\textsubscript{2}O 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\textsubscript{2}O 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\textsubscript{2}O 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\textsubscript{2}O 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\textsubscript{2}O was performed. The cumulative temperature in

Figure 4. Relative deviation from the annual mean (RDAM) of the total N\textsubscript{2}O 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\textsubscript{1/2}CM = 1/2 of the recommended N + crop residue + chicken manure.
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\textsubscript{2}O 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\textsubscript{2}O 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\textsubscript{2}O 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\textsubscript{2}O release. A general but small trend of decreasing N\textsubscript{2}O emission at higher rainfall probably exacerbated denitrification activities with more N\textsubscript{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\textsubscript{2}O 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\textsubscript{2}O 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\textsubscript{2}O emissions, which is usually followed unless automated measurement systems are established. Though the spatial variability of N\textsubscript{2}O 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\textsubscript{2}O 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\textsubscript{2}O evolution. As such, seasonal variations of N\textsubscript{2}O fluxes could mostly be explained by the availability of substrates and antecedent rainfall events in the humid tropics.

REFERENCES

Variability of N\textsubscript{2}O Emissions in the Humid Tropics


