EMISSIONS OF N₂O AND CO₂ FROM TERRA FIRME FORESTS IN RONDÔNIA, BRAZIL

DIANA C. GARCIA-MONTIEL,1 JERRY M. MELILLO,1,3 PAUL A. STEUDLER,1 HANQIN TIAN,1 CHRISTOPHER NEILL,1 DAVID W. KICKLIGHTER,1 BRIGETTE FEIGL,2 MARISA PICCOLO,2 AND CARLOS C. CERRI2

1The Ecosystems Center, Marine Biological Laboratory, Woods Hole, Massachusetts 02543 USA
2Centro de Energia Nuclear na Agricultura, Avenida Centenário 303, CEP 13416000, Piracicaba, SP, Brazil

Abstract. Nitrous oxide (N₂O) functions as a greenhouse gas in the lower atmosphere and as a destroyer of the ozone layer in the upper atmosphere. Tropical forest soils are considered the largest natural N₂O source, but the spatial pattern of the emissions is poorly understood because of the relatively small number of ground measurements and the lack of a good way to scale them. In this paper, we present a new approach for estimating the magnitude and spatial pattern of N₂O emissions from tropical forest soils of the Amazon Basin. First, we develop an empirical relationship between N₂O and CO₂ emissions from tropical soils based on seven years of field measurements made in forests of Rondônia, Brazil. Second, we combine this empirical relationship with monthly estimates of forest soil respiration across the basin from a process-based biogeochemistry model, the terrestrial ecosystem model, to estimate annual N₂O fluxes and the spatial pattern of these fluxes from the region’s undisturbed forests for the period 1980–1995. For this time interval, we estimate the average flux from the forest soils of the Amazon Basin was 7.9 × 10¹¹ g N₂O-N/yr, with the highest subregional fluxes coming from the most productive forests in the northwestern part of the basin.

Key words: Amazon basin; Brazil; CO₂ emissions; N₂O emissions; nitrogen oxide fluxes; Rondônia; terra firme forest; terrestrial ecosystem models; tropical forest.

Introduction

The gas N₂O plays important roles in the troposphere where it functions as a greenhouse gas, and in the stratosphere where it is involved in the destruction of the ozone layer. Tropical humid forests emit a large amount of N₂O (Keller et al. 1993, Verchot et al. 1999, Garcia-Montiel et al. 2001, Melillo et al. 2001) and are probably the most important natural source of this gas to the atmosphere. Microorganisms in these forest soils are responsible for a major fraction of N₂O emissions to the atmosphere each year and the major biochemical pathways responsible for N₂O production have been identified (Davidson et al. 1993, Conrad 1996, Weitz et al. 2001). At this time, we still do not have a clear understanding of how these microbial processes are influenced by the combined interaction of environmental factors, such as soil texture and structure, pH, and water-holding capacity.

Availability of nitrogen (N) and labile organic carbon (C) and soil water content are the three factors traditionally considered to control microbial denitrification (Knowles 1981). Studies in the humid tropics have usually attempted to establish relationships between indexes of soil N availability, soil water content and N₂O emissions (Matson and Vitousek 1987, Keller and Reiners 1994, Verchot et al. 1999, Davidson et al. 2000, Garcia-Montiel et al. 2001, Melillo et al. 2001), but less attention had been paid to the relationship of labile organic C with N₂O emissions. In addition, the resulting relationships of soil N availability or water content with N₂O emission usually differ among sites, mostly due to the variability introduced by the spatial heterogeneity in soil characteristics such as texture, structure, moisture-holding capacity, pH, and organic C content. These soil characteristics strongly influence the metabolic pathways of production or consumption of N₂O by nitrification and denitrification. In humid tropical forests where N is abundant, labile organic C likely limits not only denitrifiers, but also the activity of all heterotrophic microorganisms. This limitation suggests a tight linkage between the microbial processes responsible for the production and emission of N₂O and CO₂. Linking ecological controls on microbial processes to large-scale patterns of N₂O emissions requires the use of independent variables representing an integrative measurement of the microbial processes operating at the soil microscale level.

In this paper, we use a new approach for estimating N₂O emissions based on an empirically derived relationship between soil N₂O and CO₂ fluxes. Soil respiration is the combined result of root respiration and decay of soil organic matter associated with the activities of microbes and soil animals. In forest ecosystems,
where litter inputs and root exudates are the sources of labile organic carbon to soils, spatial and temporal variations of these biological variables should have a large influence on variations in N₂O and CO₂ emissions. Mean annual soil respiration rates have been shown to be positively correlated with aboveground litter production (Schlesinger 1977, Raich and Nadelhoffer 1989) and mean productivity rates (Raich and Schlesinger 1992). The connection among plant productivity, soil respiration, and N₂O emissions suggests that terrestrial ecosystem models, such as those described by Nevison et al. (1996) and Cramer et al. (1999), could be slightly modified to develop reasonable first-order estimates of N₂O emissions for a region by linking our empirical relationship between N₂O and CO₂ emissions to model estimates of soil respiration.

In this study, we first develop an empirical relationship between N₂O and CO₂ emissions from tropical forest soils based on seven years of field measurements in Rondônia, Brazil. We then combine this relationship with monthly estimates of forest soil respiration across the basin from a process-based biogeochemistry model, the terrestrial ecosystem model, to develop an annual regional estimate of N₂O emissions and to examine spatial patterns.

**METHODS**

**Study area**

To develop the empirical relationship we used data from chamber measurements of N₂O and CO₂ fluxes conducted at seven forests located in Rondônia, Brazil (Fig. 1). Two of the forest sites located at Fazenda Nova Vida, kilometer 472 of highway BR-364 in central Rondônia (10°30’ S, 62°30’ W), were intensively sampled between 1992 and 1999 such that the soil fluxes of N₂O and CO₂ were well represented for both wet and dry seasons. The other five forest sites were located in cattle ranches along a 700-km transect near highway BR-364 that connect Porto Velho to Vilhena (Fig. 1) and were sampled during October 1993 and March 1994. Precipitation along this transect ranges from 2.27 m/yr in Porto Velho to 2.09 m/yr in Vilhena (Superintendência de Desenvolvimento da Amazônia [SUDAM] 1984). Mean annual temperature varies from 24.4°C to 25.6°C in Porto Velho to 18.8°C to 20.3°C in Vilhena, with
**Figure 2.** Functional relationship between N$_2$O and CO$_2$ emissions from seven forest sites in Rondônia (modified from Garcia-Montiel et al. 2002). Open circles represent monthly emissions of N$_2$O and CO$_2$ from two forest sites located at Fazenda Nova Vida. Solid circles represent N$_2$O and CO$_2$ emissions from forest sites located in five additional ranches in Rondônia. These ranches were located in Porto Velho, Jamari, Cacaulândia, Ouro Preto, and Vilhena.

seasonal variation of $<4^\circ$C at all sites (Bastos and Diniz 1982).

Forest vegetation of Rondônia has been classified as ombrotrophic open submontane forest (RadamBrasil 1978) and consists of open moist tropical forest with a large number of palm trees. The end of the transect at Vilhena represented the transition between closed forest and campo cerrado vegetation. All other forests were typical of most remaining terra firme forest in Rondônia. The information provided by ranch owners indicated that an average of 3 trees/ha was removed from all the forests by selective logging 10 years prior to our sampling. This level of disturbance is very typical of the accessible forests that remain in large ranches in Rondônia (Pedlowski et al. 1997).

The two forest sites from Nova Vida have been used in previous studies to understand the effect of the conversion of forest to pasture on C, N, and P stocks and dynamics (Moraes et al. 1995, Neill et al. 1995, 1997, Garcia-Montiel et al. 2000) and trace gas emissions (Feigl et al. 1995, Steudler et al. 1996, Garcia-Montiel et al. 2001, Melillo et al. 2001). All sites used in this study were selected only in areas of flat or gentle rolling topography. Soil types found along the transect included the dominant soils in the Brazilian Amazon Basin. These are dystrophic red–yellow podzolics (Udults), which cover $\sim22\%$ of the Brazilian Amazon; yellow Latosols (Udoxes), which cover $18\%$; and eutrophic red and red-yellow podzolics (Udalfs), which cover $4\%$ (Moraes et al. 1995). Soil texture along the transect varied from high-clay, yellow Latosols (Hapludoxes) with clay content between 67% and 76% at Vilhena to sandy red-yellow podzolics (Paleudults) with sand contents between 70% and 85% at Nova Vida and Ouro Preto.

**Field measurements**

**Sample collection.**—Fluxes of N$_2$O and CO$_2$ were measured 13 times between 1992 and 1999 in one of the two forest sites located at Fazenda Nova Vida. The second forest site at Fazenda Nova Vida was measured six times during the years 1992 and 1993. The other forest sites along the transect were sampled only twice, in October 1993 and March 1994, to capture low and high soil moisture conditions (Zeng 1999). The sampling protocol for the two forest sites at Fazenda Nova Vida has been described in previous publications (Garcia-Montiel et al. 2001, Melillo et al. 2001) and the N$_2$O and CO$_2$ sampling design at the other forest sites along the transect followed this protocol. At each site, we used three chambers and at each sampling date collected a total of six measurements of CO$_2$ and N$_2$O, three samples were collected during the early morning (0600 to 0900 hours) and the other three samples were collected during the afternoon (1230 to 1430 hours). This sampling protocol was designed to capture fluxes during times of minimum and maximum daily temperatures. Mean daily emissions were calculated by averaging the six measurements and then scaled to estimate monthly emissions.

**Determination of N$_2$O and CO$_2$ fluxes.**—Fluxes of N$_2$O and CO$_2$ were measured using static chambers from 1992 to 1996 and using recirculating chambers between 1998 to 1999. At each sampling site, three polyvinyl chloride (PVC) anchor rings were inserted 2 cm into the soils and they were inserted in place at least one or two days before measurements were begun.

For 1992 to 1996, gas measurements were conducted by placing a PVC chamber top on the anchor ring to create a head-space volume of $\sim8$ L. The first gas sample was obtained immediately after placing the chamber top on the anchor by collecting headspace gas with 10- or 20-mL syringes equipped with stopcocks. Then four additional samples were collected 5, 10, and 20 min after incubation started. The fluxes of N$_2$O and CO$_2$ were estimated by the changes in headspace gas concentrations. During this sampling period, both N$_2$O and CO$_2$ concentrations were simultaneously analyzed by gas chromatography with $^{63}$Ni electron capture detector (Bowden et al. 1990) and using certified calibration standards of N$_2$O and CO$_2$ in N$_2$ (Scott-Specialty Gases, Plumsteadville, Pennsylvania, USA) for calibration. Fluxes were always calculated by linear regression of the incubation time and N$_2$O or CO$_2$ concentrations using the linear part of the curve.
For 1998 to 1999 we used a different sampling scheme for CO$_2$ measurements. Instantaneous measurements were obtained with a Li-Cor model 6252 (Li-Cor, Lincoln, Nebraska, USA) infrared gas analyzer for CO$_2$ (IRGA) using a recirculating chamber and connected to a CR10X Campbell data logger. The CO$_2$ fluxes were calculated from the rate of increase CO$_2$ concentrations using the steepest linear portion of the curve. Measurements of changes in N$_2$O concentrations in the chambers were synchronized with the field measurements of CO$_2$ by collecting headspace gas with syringes following the same protocol as before. Nitrous oxide concentrations were then analyzed in the field laboratory with a $^{63}$Ni electron capture detector.

During each sampling period, we measured temperatures of ambient air ($-1$ m above the ground), chamber air, and at 2, 5, and 10 cm depths. Barometric pressure was also measured at the beginning of each incubation and used to correct N$_2$O and CO$_2$ concentrations.

**Statistical analysis**

To develop the empirical relationship between N$_2$O and CO$_2$ emissions, we used a linear model II regression analysis (Sokal and Rohlf 1995). This analysis was used because both N$_2$O and CO$_2$ were subject to random sampling error. To explore relationships of N$_2$O emissions with N availability indices and soil moisture content we used SYSTAT 9.0 (SPSS 1999).

**Development of regional estimates of N$_2$O emissions from Amazonian forests**

We used the terrestrial ecosystem model (TEM 4.2), to extrapolate our empirical relationship across tropical forests in the Amazon Basin (Appendix A). This process-based model uses spatially referenced information on climate, elevation, soils, and vegetation to make monthly estimates of a variety of carbon and nitrogen pools and fluxes in terrestrial ecosystems (Melillo et al. 1993, Tian et al. 1999, McGuire et al. 2001). The model has recently been shown to provide reasonable estimates of carbon fluxes at two forest sites in the Amazon Basin (Tian et al. 1998).

Because TEM does not directly simulate soil respiration, we estimated soil respiration with the following equation:

\[
\text{soil respiration} = R_H + \alpha R_A
\]

where $R_H$ refers to the decomposition of detritus associated with the heterotrophic respiration of soil microbes and fauna as estimated by TEM, $R_A$ refers to respiration from both above- and belowground components of living vegetation as estimated by TEM, and $\alpha$ is the fraction of $R_A$ that is root respiration. We based $\alpha$ on estimates made by M. Ryan (personal communication). Working in tropical forests of Costa Rica and Hawai'i, he observed a range of $\alpha$ of 0.30–0.40. Based on our analyses, this range of $\alpha$ corresponds to root respiration fluxes being between 27% to 35% of total soil respiration. These percentages are within the range of...
TABLE 1. Emissions of $N_2O$ and $CO_2$ (± 1 std) from forests located in cattle ranches along highway BR-364, Rondônia, Brazil.

<table>
<thead>
<tr>
<th>Location</th>
<th>$N_2O$ Flux (µg m$^{-2}$ h$^{-1}$)</th>
<th>$CO_2$ Flux (mg C m$^{-2}$ h$^{-1}$)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porto Velho</td>
<td>25.2</td>
<td>163.92</td>
<td>2</td>
</tr>
<tr>
<td>Jamari</td>
<td>34.5</td>
<td>151.09</td>
<td>2</td>
</tr>
<tr>
<td>Cacaualdãia</td>
<td>34.3</td>
<td>159.01</td>
<td>2</td>
</tr>
<tr>
<td>Nova Vida 1</td>
<td>27.3 (+ 4.6)</td>
<td>148.1 (+ 9.7)</td>
<td>13</td>
</tr>
<tr>
<td>Nova Vida 2</td>
<td>19.2 (+ 7.0)</td>
<td>155.5 (+ 18.5)</td>
<td>6</td>
</tr>
<tr>
<td>Ouro Preto</td>
<td>30.5</td>
<td>144.7</td>
<td>2</td>
</tr>
<tr>
<td>Vilhena</td>
<td>28.1</td>
<td>161.4</td>
<td>2</td>
</tr>
</tbody>
</table>

*Note: No standard error is reported when n = 2. Fluxes of $N_2O$ and $CO_2$ were measured 13 times between 1992 and 1999 in one of the two forest sites located at Fazenda Nova Vida. The second forest site at Fazenda Nova Vida was measured six times during the years 1992 and 1993. The other forest sites along the transect were sampled twice, in October 1993 and March 1994, to capture the seasonality of the emissions.*

reported in recent literature reviews (Raich and Schlesinger 1992, Hanson et al. 2000). To examine the influence of this uncertainty on estimates of $N_2O$ emissions, we conducted a sensitivity analysis assuming that $\alpha$ equaled 0.30, 0.35, and 0.40.

RESULTS AND DISCUSSION

Emissions of $CO_2$ and $N_2O$ along the transect

Nitrous oxide emissions from the forest soils along the transect ranged between 21 to 35 µg m$^{-2}$ h$^{-1}$ (Table 1). The lowest $N_2O$ emissions were observed at Fazenda Nova Vida, while the largest emissions were observed in the forests from Jamari and Cacaualdãia (Table 1). Emissions of $CO_2$ from forest soils ranged between 144 mg·m$^{-2}$·h$^{-1}$ at Ouro Preto to 164 mg·m$^{-2}$·h$^{-1}$ at Porto Velho (Table 1).

We conducted correlation analysis to test for significant relationships between $N_2O$ emissions and either soil nutrients or WFPS, and we found none. This is consistent with previous work conducted in forests at Fazenda Nova Vida (García-Montiel et al. 2001).

Relationships between $N_2O$ and $CO_2$ emissions from terra firme forests

In situ measurements of $N_2O$ and $CO_2$ from forests at Nova Vida showed a strong correlation. Based on this correlation, we derived a highly significant ($P < 0.0001$) linear relationship ($N_2O = -4.16 + 0.18CO_2$). According to this relationship the soil $CO_2$ emissions explained 69% of the variability observed in $N_2O$ emissions.

To examine the generality and predictive potential of this relationship, we tested for its statistical significance after including the $N_2O$ and $CO_2$ emissions measured from the other five forest sites located along the transect (Table 1). After inclusion of these points, the parameters changed very little ($N_2O = -4.78 + 0.20CO_2$). The relationship was still highly significant ($P < 0.0001$) and the $CO_2$ emissions still explained 62% of the variability in $N_2O$ fluxes (Fig. 2).

Our working hypothesis is that the relationship between $N_2O$ and $CO_2$ emissions from tropical soils is a function of the fact that both are dependent on the availability of labile carbon. Aerobic respiration, which uses $O_2$ as terminal electron acceptor, and denitrification, which uses NO$_3^-$ as terminal electron acceptor, are both heterotrophic microbial metabolisms that use electron donors from organic carbon to power the reduction of $O_2$ or NO$_3^-$, respectively (Gottschalk 1986, Madigan et al. 2000). Soil microorganisms in general, are mainly limited by carbon and energy (Knowles 1981). Therefore, it is not surprising that in humid tropical forests, where NO$_3^-$ is usually abundant, denitrification is more likely controlled by the supply of readily decomposable organic carbon.

The relationship between $N_2O$ and $CO_2$ is well documented for cultivated soils (Burford and Brenner 1975). In natural ecosystems, limitations of organic C availability on denitrification rates have been demonstrated in the riparian zones of temperate forests (Hill et al. 2000), and in the upland of tropical forest area of Costa Rica (Nobre et al. 2001). Hill et al. (2000) clearly documented the occurrence of high-denitrification spots where nitrate-rich ground water met carbon-rich areas. Nobre et al. (2001) showed that the addition of sugar to a tropical soil stimulated $N_2O$ production.

Regional estimates of $N_2O$ emissions from Amazonian forests

Overall, we estimate that undisturbed Amazonian forests emit an average of $7.9 \times 10^{11}$ g N$_2O$-N/yr during the years 1980–1995 if we assume $\alpha$, the fraction of $R_a$ that is root respiration, equals 0.35. This average basin-wide estimate decreases to $7.4 \times 10^{11}$ g N$_2O$-N/yr if $\alpha$ is 0.30 and rises to $8.3 \times 10^{11}$ g N$_2O$-N/yr if $\alpha$ is 0.40. These estimates are very similar to the $8.0 \times 10^{11}$ g N$_2O$-N/yr previously estimated for the Amazon Basin for the year 1997 by Melillo et al. (2001) using a totally different modeling approach, but higher than $5.0 \times 10^{11}$ g N$_2O$-N/yr reported by Potter et al. (1998) for tropical forests which only included the Brazilian portion of the basin.

Nitrous oxide emissions were spatially variable across the basin. For the case when $\alpha$ was 0.35, $N_2O$ emissions of the $0.5^\circ \times 0.5^\circ$ grid cells ranged between 0 and 268 mg N$_2O$-N·m$^{-2}$·yr$^{-1}$ with a basin-wide mean of 162 mg N$_2O$-N·m$^{-2}$·yr$^{-1}$. The highest $N_2O$ emissions were estimated in the northwestern portion of the Amazon Basin (Fig. 3). Emissions decreased as environmental conditions became drier to the east and south.

Our basin-wide estimates of annual $N_2O$ emissions show small year-to-year variations, 7.7–8.1 $\times 10^{11}$ g N$_2O$-N/yr when $\alpha = 0.35$, during the period of 1980–
1995. This is related to the fact that TEM simulations also show little year-to-year variations in $R_H$ (Tian et al. 1998). Thus, our regional extrapolations also show little influence of El Niño events on annual N$_2$O emissions from undisturbed Amazonian forests. This result is similar to what has been previously reported by Melillo et al. (2001).

To evaluate the generality of our empirical relationship across the Amazon Basin, we compared our spatially explicit estimates of N$_2$O to field observations in areas of the basin outside of Rondônia where measurements have been made for a year or more. Our estimated annual N$_2$O emission value for the Manaus region (146 mg N$_2$O-N m$^{-2}$ yr$^{-1}$) was very close to the average value reported from two field studies by Luizão et al. (1989; 190 mg N$_2$O-N m$^{-2}$ yr$^{-1}$) and Coolman (1994; 128 mg N$_2$O-N m$^{-2}$ yr$^{-1}$). However, in Paraminhas, our estimated N$_2$O emissions (143 mg N$_2$O-N m$^{-2}$ yr$^{-1}$) substantially underestimated those reported from Fazenda Vitória (243 mg N$_2$O-N m$^{-2}$ yr$^{-1}$), the most well-studied site in the area (Verchot et al. 1999). It is possible that this site has some unique biogeochemical characteristics. For example, it has one of the highest soil respiration rates ever measured in a tropical forest site (Davidson et al. 2000).

Future directions

To conduct more rigorous tests of the predictive capabilities of our approach, we need additional long-term field observations of N$_2$O fluxes from intact forests in the Amazon Basin, such as those currently becoming available from the Large-scale Biosphere–Atmosphere Experiment in Amazonia (LBA) project.

Indeed, this data would include measurements of concurrent N$_2$O and CO$_2$ emissions covering the spatial and temporal patterns along climatic gradients. In addition, we need better characterization of root respiration vs. heterotrophic respiration to improve our ability to apply different ecosystem models to extrapolate the relationship between N$_2$O and CO$_2$ fluxes from soils. However, this study suggests that estimating N$_2$O emissions from soil respiration measurements provides a useful approach for developing regional estimates of N$_2$O emissions and for examining spatial patterns of these emissions across a region.

Acknowledgments

We thank M. Ryan (USDA Forest Service, Fort Collins, Colorado) for supplying the information on root respiration as a proportion of total plant respiration for tropical sites. We also thank to S. Pan for assistance with the GIS map, E. Rastetter for statistical advice, and João Arantes, Jr., who generously allowed us to work on his land. This study was supported by the National Aeronautics and Space Administration as a part of the Large-scale Biosphere–Atmosphere Experiment in Amazonia.

Literature Cited


**APPENDIX**

A description of the terrestrial ecosystem model is available in ESA’s Electronic Data Archive: Ecological Archives A014-025-A1.