Biogeochemistry **64:** 319–336, 2003.

Nitrogen oxide emissions following wetting of dry soils in forest and pastures in Rondônia, Brazil

DIANA C. GARCIA-MONTIEL[1,*], PAUL A. STEUDLER[1], MARISA PICCOLO[2], CHRISTOPHER NEILL[1], JERRY MELILLO[1] and CARLOS C. CERRI[2]

*[1]Marine Biological Laboratory, The Ecosystems Center, Woods Hole, MA 02543, USA; [2]Centro de Energia nuclear na Agricultura, Avenida Centenário 303, Piracicaba, CEP 13416000, Brazil; *Author for correspondence (e-mail: dgarcia@mbl.edu)*

Received 28 March 2002; accepted in revised form 6 April 2002

Key words: Amazon, Deforestation, N oxide gases, Seasonal pulse, Tropical forest and pastures

Abstract. Rains at the end of the dry season can trigger increases in emissions of nitric oxide (NO) and nitrous oxide from forest and pasture soils in the Amazon Basin. The relative importance of the rain-stimulated emissions in the seasonal and annual budgets of these nitrogen gases for forests and pastures in the western Amazon is not well established. We measured soil emissions of NO and N_2O from a forest and two pastures, 11 and 26 years old, after a simulated rain event. Wetting the soil resulted in very small pulses of NO or N_2O from forest soils and no significant NO or N_2O pulses from the pastures. We estimated that in the forest, the amounts of each gas emitted from pulses during the dry to wet transition period represented 3.4% of the NO and 1.8% of the N_2O dry-season emissions, but amounted to less than 2% of the annual emissions of either gas. Total N oxide emissions of 5.6 kg N/ha/yr from the forest were nearly evenly divided between NO (42%) and N_2O (58%). The emissions of NO were evenly distributed over the wet and dry seasons, while over 84% N_2O fluxes occurred during the wet season.

Introduction

Soil wetting after prolonged dryness in tropical forests has been demonstrated to affect the abiological and biological production of nitric and nitrous oxide gases (Davidson et al. 1993; Breuer et al. 2000). It has been postulated that low microbial activity during prolonged soil dryness results in an accumulation of inorganic N (Shields et al. 1974). Soil accumulation of NH_4^+, NO_2^- and NO_3^- may occur in thin water films of microsites near oxidizing sites. Upon soil wetting, soil microbes can quickly use these pools, and produce pulses of N oxide gases.

This process has been studied in tropical dry forests of Central America (Davidson et al. (1991, 1993); García-Méndez et al. 1991) and several temperate ecosystems in North America (Davidson 1992). In the Amazon, the short-term dynamics associated with the drying and wetting of soils in seasonally moist tropical forests and pastures may be especially important because this region experiences prolonged dry periods during which there is little or no rain.

Tropical humid forests have generally high rates of net mineralization and net nitrification that can lead to the accumulation of NH_4^+ and NO_3^- during dry periods (Neill et al. 1995). When tropical humid forests are converted to pastures, N availability in soil decreases (Prather and Ehhalt 2001; Neill et al. 1995; Van Gestel et al. 1993). This has been associated with lower N oxide emissions from pastures (Keller and Reiners 1994; Van Gestel et al. 1993; Garcia-Montiel et al. 2001; Melillo et al. 2001). However, by the end of the dry season, an accumulation of inorganic N pools can occur. This could result in pulses of N oxide emissions from pastures with the onset of precipitation. These pulses have the potential to represent a sizeable fraction of the total annual emissions from the Amazonian pastures.

We investigated how changes in soil moisture affect the fluxes of NO, N_2O and CO_2 from forest and pasture soils in the southwestern Brazilian Amazon. The main objectives were to: 1) measure the short-term dynamics of soil emissions of NO, N_2O, and CO_2 in forest and pasture soils associated with soil wetting after prolonged dryness; and 2) quantify the contribution of the pulses of N oxide fluxes resulting from soil wetting to dry season and annual fluxes.

Study area

We conducted this study at Fazenda (Ranch) Nova Vida, km 472 of highway BR-364 in central Rondônia (10°30′ S, 62°30′ W). Climate of the area is characteristic of humid tropical forest, with an annual precipitation of 2270 mm. The precipitation pattern is characterized by a dry season starting by the end of May and lasting until September (Figure 1). This dry period can be interrupted by sporadic rain events. Mean annual maximum and minimum temperatures are 25.6 and 18.8 °C, respectively, with a seasonal variation of approximately 4 °C (Bastos and Diniz 1982).

We used a forest and two pastures, one created in 1987 and the other in 1972. At the time of this study the pasture created in 1987 was 11 years old and the pasture created in 1972 was 26 years old. In these pastures rates of net N mineralization and net nitrification have decreased compared with the forest (Neill et al. 1995). These sites were part of previous studies of the effect of the conversion of forest to pasture on C, N, and P stocks and dynamics (Neill et al. (1995, 1997); Garcia-Montiel et al. 2000) and trace gas fluxes (Feigl et al. 1995; Steudler et al. 1996; Garcia-Montiel et al. 2001; Melillo et al. 2001; Steudler et al. 2002). Forest vegetation consisted of open moist tropical forest with a large number of palm trees. Forest biomass at the time of sampling at Nova Vida was 313 ton ha^{-1} (de Graça 1997). This forest was altered by selective logging, which removed 1–3 trees/ha during 1987–1989. The pastures were formed by slash and burning of the original forest with no intermediate cropping phase, soil tilling, chemical fertilization or liming. Both pastures were planted with *Brachiaria brizantha* (Hochst) Stapf. All sites used in this study were in areas at an elevation of approximately 150 m with minimal relief. Soils contained between 20–30% clay and were classified as red-

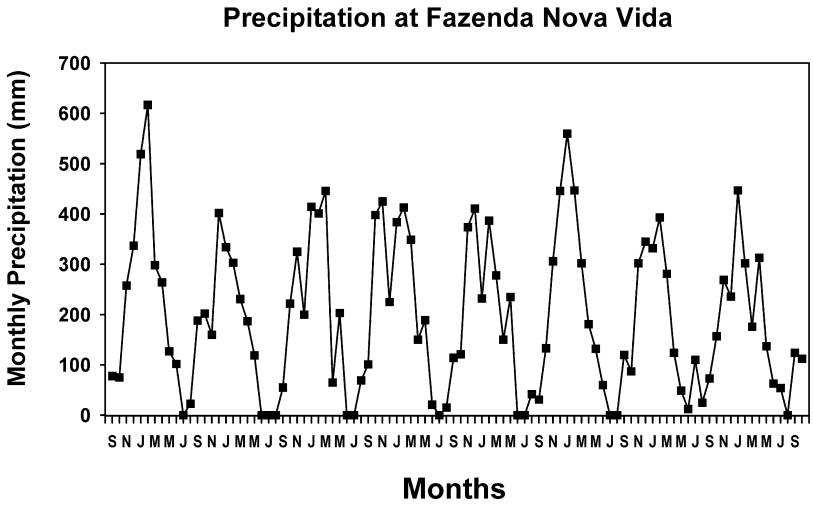

Figure 1. Monthly average precipitation at Fazenda Nova Vida, Rondônia, for the period 1992–2001.

yellow podzolic latosol in the Brazilian classification and as Kandiudult in the U.S. classification (Moraes et al. 1995).

Methods

Experimental design

We established five 1×2-m plots in the forest and in the two pastures. One half of each plot was used for gas flux measurements; the other half was used for soil coring to determine soil water content and inorganic N pools. We randomly selected three of the five established plots for irrigation. The other two non-irrigated plots were used as controls. On August 18,1998, we simulated a 30 mm of rain in the 11-year-old pasture by sprinkling 60 L of stream water in each plot. Using stream water to irrigate the plots did not cause N fertilization of soils because concentrations of NH_4^+ and NO_3^- (0.74 and 2.09 μM/L) were very small relative to the concentrations in the soil solution. The simulation of rain in the forest was conducted on August 20th and on August 22nd of 1998, in the 26-year-old pasture. The amount of the simulated rain was in the range of the first rain that generally occurs near the end of the dry season. At each site we measured fluxes of NO, N_2O and CO_2 between 1500–1700 hours the day before the start of the irrigation, and again at about 0600 hours immediately before irrigation. Addition of water to the plot usually took 7–8 minutes. We waited about 20 minutes to allow water to percolate into the soil, and then made a series of measurements at 1–1.5 hour intervals for the next 12 hours to follow the time course of the emissions. Fluxes were measured once more the next day, approximately 30–34 hours after irrigation. Control plots were mea-

sured four times over the whole experiment: 1) the day before irrigation, 2) the morning immediately before irrigation, 3) at approximately mid-day on the day of irrigation and 4) the next day at the end of the experiment.

On the night of August 6, 12 days prior to the start of the irrigation experiment, there was a rain event that delivered 17.5 mm of water (measured at the 11-year-old pasture site under open canopy). These sporadic rain events that occur during the dry season can be very patchy and did not occur in all our experimental sites. A field inspection conducted the next day at about 0600 hours indicated that no rain had fallen on the 26-year-old pasture and the rain had little affect on the forest and the 11-year-old pasture soils.

Following the moisture manipulations, we also measured the trace gas emissions after the second rain, which occurred the night of August 26th and delivered 42 mm of water. These measurements were conducted the next day (August 27th), approximately 13 and 17 hours after the rain ended in the 11-year-old pasture and forest, respectively. At each site we measured a total of five plots, two of which were the same plots previously designated as the non-irrigated controls during the irrigation experiment. The other three plots were located in the control plots of an ongoing N and P fertilization experiment (Steudler et al. 2002) adjacent to the site of the wetting experiment. In these plots, pre-rain measurements had been conducted about 10 days prior to the second rain. The measurements made on the control plots during the wetting experiment were used as the pre-rain measurements. These pre-rain measurements represented the fluxes and N cycling conditions expected by the end of the dry season (Garcia-Montiel et al. 2001).

Determination of NO, N_2O and CO_2 fluxes

Fluxes of NO, N_2O and CO_2 were measured using re-circulating chambers. In each plot, one polyvinyl chloride (PVC) anchor ring was inserted 2 cm into the forest or the pasture soils. Anchor rings were installed at least two days before measurements. Gas measurements were conducted by placing a PVC chamber top on the anchor ring to create a chamber with 7.0–8.5 L headspace. Gas fluxes were then measured by the changes in headspace gas concentrations. Measurements lasted 20 minutes.

Fluxes of NO and CO_2 were instantaneously measured with a Unisearch Associates LMA-4 NO_2 analyzer for NO (Unisearch Associates Inc. 1996) and a LI-COR model 6252 infrared gas analyzer for CO_2 (IRGA), both connected to a CR10X Campbell data logger. Gases were re-circulated throughout 6 mm Teflon tubes connected from the chamber top to the LMA-4 NO_2 analyzer and to the LI-COR. Our design used the LICOR pumping system to re-circulate air at 1 L/min through the Teflon line connected to the chamber top, while the NO analyzer subsampled this same air flow at about 400 mL/min and returned the air to the re-circulating air stream. The sample air that entered the analyzer was oxidized to NO_2 by reaction with CrO_3. The sample air was then passed across a fabric wick saturated with luminol solution, which is oxidized when in contact with NO_2, to produce chemiluminiscence. This chemiluminiscence was measured by a photomulti-

plier tube and is directly proportional to the mixing ratio of NO_2 (Unisearch Associates Inc. 1996). The effect of temperature changes on the luminol reaction was automatically corrected by the instrument (Unisearch Associates Inc. 1996). Because high humidity affects the lifetime of the CrO_3 catalyst, we modified the instrument to increase the efficiency of water removal from the sample air stream by increasing the pressure differential across the Nafion shell dryer. We also connected a silica gel drying tube to the outer shell of the Nafion dryer. These modifications resulted in stable conversion efficiencies for at least 50 hours of use under 25–30 °C temperature and approximately 90% relative humidity. Fluxes were calculated from the rate of increase or decrease of NO or CO_2 concentrations using the steepest linear portion of the curve. This linear phase usually started 1 or 2 minutes after placing the chamber top on the anchor; however, very fast linear increases in NO concentration were often obtained in half a minute after placing the chamber top on the anchor.

The LMA-4 NO_2 analyzer was calibrated using a 49.2 ppmv NO standard obtained by dilution of a 1.032 ppmv NO standard in O_2 free N_2 (Scott-Martin, California) with NO/NO_2 free air. NO/NO_2 free air was produced by passing ambient air through a drierite scrubber to remove water vapor and through an ascarite scrubber to remove ambient NO and NO_2. The NO/NO_2 free scrubbing system produced air that contained NO concentrations of $\leqslant 0.006$ ppbv. The IRGA was calibrated using an 826 ppmv CO_2 standard (Scott-Martin, California). Both, the LMA-4 NO_2 analyzer and the IRGA were calibrated in the laboratory before and after each day of sampling and variations between calibrations were usually within ± 10% for NO and less than ± 1% for CO_2

Measurements of changes in N_2O concentrations in the chambers were synchronized with the field measurements of NO and CO_2. Headspace gas samples were collected for N_2O at the beginning of the incubation and then after 5, 10 and 20 minutes, using 10 mL BD syringes equipped with stopcocks. Nitrous oxide concentrations were analyzed within 10 hr after collection at Nova Vida using an electron-capture gas chromatograph with a detector temperature of 310 °C (Bowden et al. 1990). A certified standard of 0.985 ppmv N_2O in N_2 (Scott-Specialty gases, Pennsylvania) was used for calibration and fluxes were calculated by linear regression of incubation time and N_2O concentrations using the linear part of the curve.

Shaded ambient air (about 1 m above the ground), inside chamber air and soil temperature at 2, 5 and 10 cm depth, were measured during each incubation. Because of large temperature variation in pastures, readings were conducted before and after the incubation and then average values were used for flux calculations. Barometric pressure was also measured at the beginning of each incubation.

Inorganic n pools and soil moisture content

Soil samples were collected from the 0–2, 2–5, and 5–10 cm soil depths at each of the 1 × 1-m subplots assigned for soil coring using a 2.5 cm diameter soil corer. Soil sampling was synchronized with the gas flux measurements. No soil was collected the day before irrigation was conducted, but it was collected early in the

morning before irrigation started. All soil samples were prepared the same day of collection by removing roots and stones and mixing by hand. Extraction of NH_4^+ and NO_3^- was done with 2 mol/L KCl as described in Piccolo et al. (1994). Gravimetric moisture content was obtained by drying a soil subsample to constant weight at 105 °C. Final N pools were corrected for moisture content and reported on mass of oven dry soil. Soil water content was converted to % water filled-pore space (WFPS) using bulk density and particle density.

Results

Changes in % WFPS and soil temperature during the wetting experiment

In forest soils, the simulation of 30 mm of rain produced a very little increase in % WFPS of the 0–2 cm soil depth. At the 2–5 cm depth % WFPS increased from about 36% to 50% just 20 minutes after irrigation. In the 5–10 cm depth a similar increase occurred but with a delay (Figure 2a). The same 30 mm of water addition to pasture soils caused larger increases in % WFPS at all depths (Figure 2c and 2e), but as in the forest the largest increase occurred in the 2–5 cm of soil depth.

Soil temperature in control plots of the forest soil never exceeded 27 °C (Figure 2b) and water addition to the irrigated forest plots maintained soil temperature about 2 °C below the soil temperature in control plots. In pastures, soil temperatures were higher and more variable than in forest soils (Figure 2d and 2f). Maximum temperatures in the 0–2 cm depth of the non-irrigated pasture plots ranged between 29–33 °C (Figure 2d and 2f).

Changes in inorganic n pools

In the forest, soil NH_4^+ pools from non-irrigated and irrigated plots were always lower than the NO_3^- pools at all soil depths (Figure 3a and 3b). The forest NO_3^- pools were greatest in the 0–2 cm depth (Figure 3b). In contrast, NH_4^+ pools in non-irrigated and irrigated plots of pasture soils were always larger than NO_3^- pools at all soil depths (Figure 3c, 3d, 3e and 3f). The pasture NO_3^- pools were very small at all soil depths from both pastures (Figure 3d and 3f). During the irrigation experiment, neither forest nor pastures soils showed a clear trend in the size of inorganic N pools (Figure 3).

Effect of irrigation on NO, N_2O and CO_2 fluxes

Prior to irrigation of forest soils, fluxes of NO were more than 20 times higher than fluxes of N_2O, which usually showed net uptake (Figure 4a). Two and one half-hours after irrigation, NO fluxes showed a 4.3-fold increase relative to the pre-treatment fluxes, but eight hours after irrigation, NO fluxes decreased to the pre-treatment level (Figure 4a). Nitrous oxide fluxes also showed a 10.2-fold increase

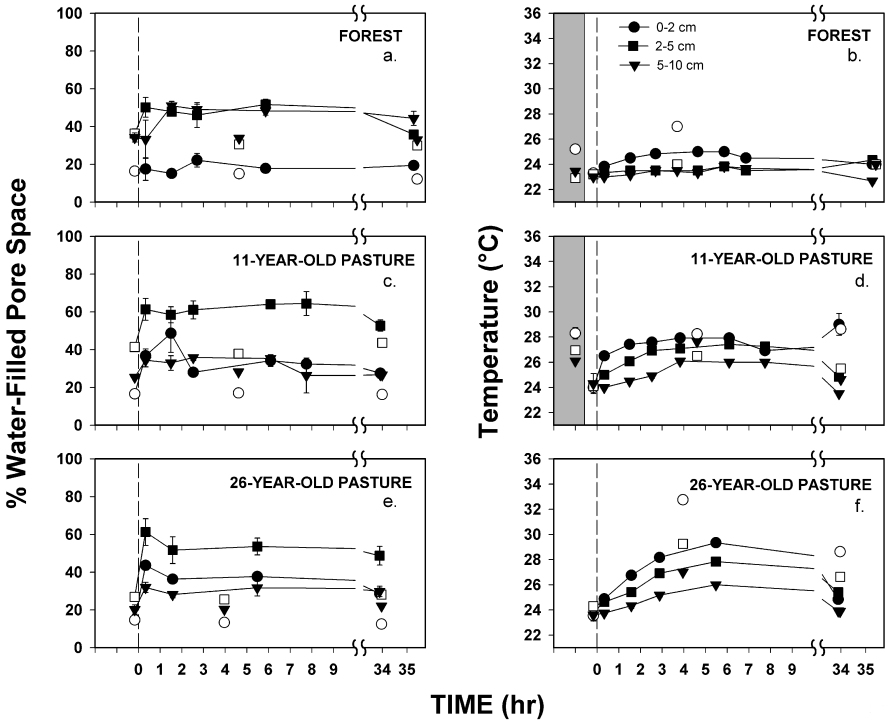

Figure 2. Percent water filled-pore space (a, c and e) and soil temperature (b, d and f) at 0–2, 2–5 and 5–10 cm soil depths during the irrigation experiment conducted in a forest and 11- and 26-year-old pastures at Nova Vida. Close symbols represent % WFPS or temperatures in irrigated plots and eliminate open symbols represent % WFPS or temperatures in non-irrigated control plots. Shaded areas represent measurements made the day before the irrigation experiment started and the vertical dashed line indicates when water was added to the soil. Error bars are standard errors.

relative to the pre-treatment N_2O level (Figure 4a). As with NO, forest fluxes of N_2O returned to nearly pre-treatment levels eight hours after irrigation.

In both pastures, soil fluxes of NO from the non-irrigated plots showed net uptake, while pre-treatment fluxes of N_2O were approximately 10 times larger than fluxes of NO (Figure 4b and 4c). After addition of water to pasture soils, changes in NO fluxes were relatively small compared to those observed in the forest (Figure 4b, 4c). In contrast to NO fluxes, fluxes of N_2O were different between the two pastures. In the 11-year-old pasture, we observed no clear trends in N_2O emissions after addition of water to soil (Figure 4b), but in the 26-year-old pasture N_2O fluxes showed a much clearer trend. Twenty minutes after irrigation, N_2O fluxes from the 26-year-old pasture increased from 10.2 μg N m^{-2} hr^{-1} to 30.6 μg N m^{-2} hr^{-1}, but returned to pre-treated levels three hours after the water was added.

At all three sites, fluxes of CO_2 showed an immediate increase in response to irrigation (Figure 5a, 5b and 5c). Even in the forest, where changes in % WFPS were relatively small compared to the pastures, the CO_2 response was large. Twenty

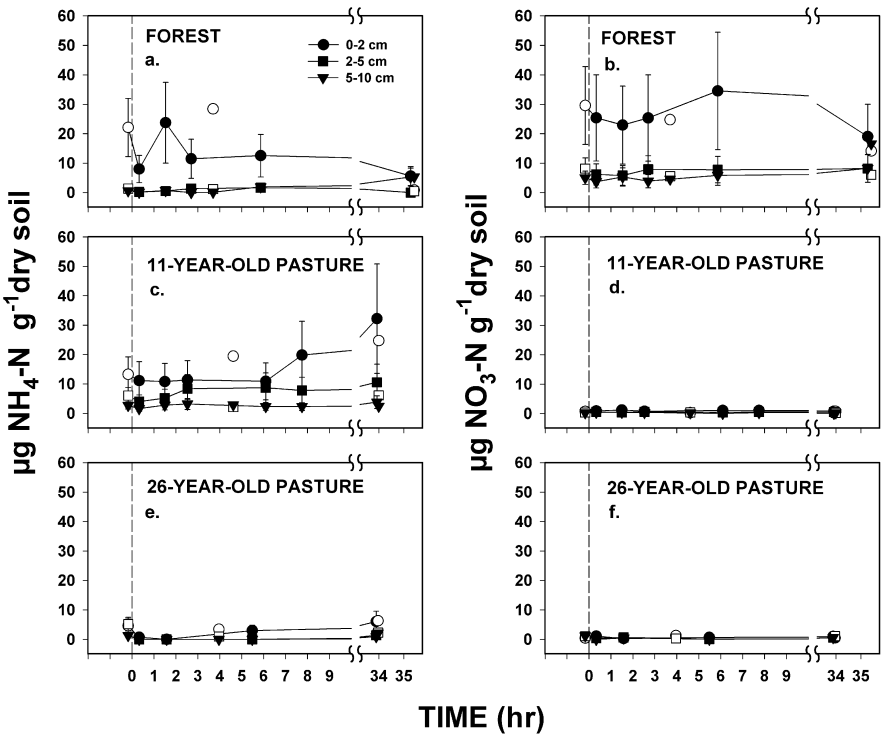

Figure 3. Ammonium (a, c and e) and NO_3^- (b, d and f) pools at 0–2, 2–5, and 5–10 cm soil depths during the irrigation experiment conducted in a forest and 11- and 26-year-old pastures at Nova Vida. Close symbols represent N pools in irrigated plots and open symbols represent N pools in non-irrigated control plots. Vertical dashed line indicates when water was added to the soil. Error bars are standard errors.

minutes after addition of water, CO_2 increased by about 1.8-fold in the forest and pastures, and this response was of longer duration than the responses to irrigation observed in NO or N_2O fluxes. Twenty-eight hours after irrigation, forest soils were still emitting 80% more CO_2 than the corresponding control (Figure 5a). The 11- and 26-year-old pasture soils were still emitting 69% and 44% more CO_2 than the controls (Figure 5b and 5c).

Effect of the second rain on % WFPS, N pools and trace gas emissions

Percent WFPS at the end of the dry season was the lowest in the 0–2 cm depth of forest and pasture soils (Table 1). Several hours after the rain, % WFPS increased at all soil depths at both sites, but the observed increase was larger in pasture soils (Table 1).

In forest soils, end of the dry season pools of NH_4^+ and NO_3^- were the greatest in the 0–2 cm depth (Table 1), while in pasture soils only NH_4^+ was high in the 0–2 cm depth. In contrast to the forest, the NO_3^- pools in the pasture soils was very

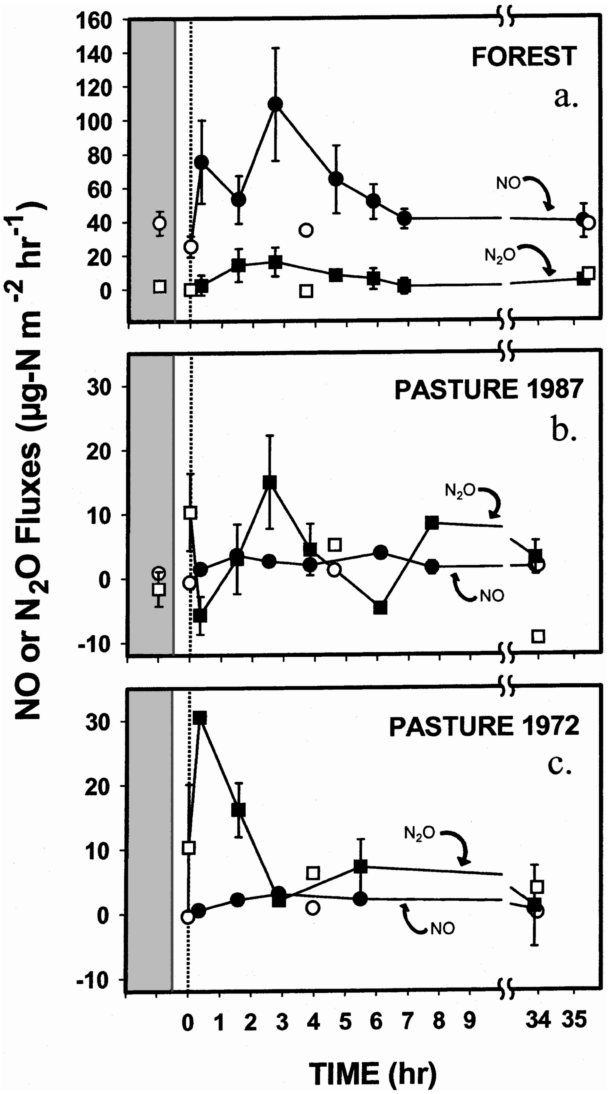

Figure 4. Fluxes of NO (●) and N_2O (□) during the irrigation experiment conducted in a forest (a) and 11- and 26-year-old pastures (b and c) at Nova Vida. Closed symbols represent fluxes from irrigated plots and open symbols represent fluxes from non-irrigated control plots. Shaded areas indicate measurements made the day before the irrigation experiment started and the vertical dashed line indicates when water was added to the soil. Error bars are standard errors.

small at all soil depths (<0.5 μg N gds^{-1}). Several hours after the rain, the NH_4^+ pool showed a 1.4-fold increase in the 0–2 cm depth of forest and pasture soils and a 5-fold increase in the 5–10 cm depth of only forest soils (Table 1). In contrast, the NO_3^- pool showed little variation between the end of the dry season and several hours after the rain at both sites (Table 1).

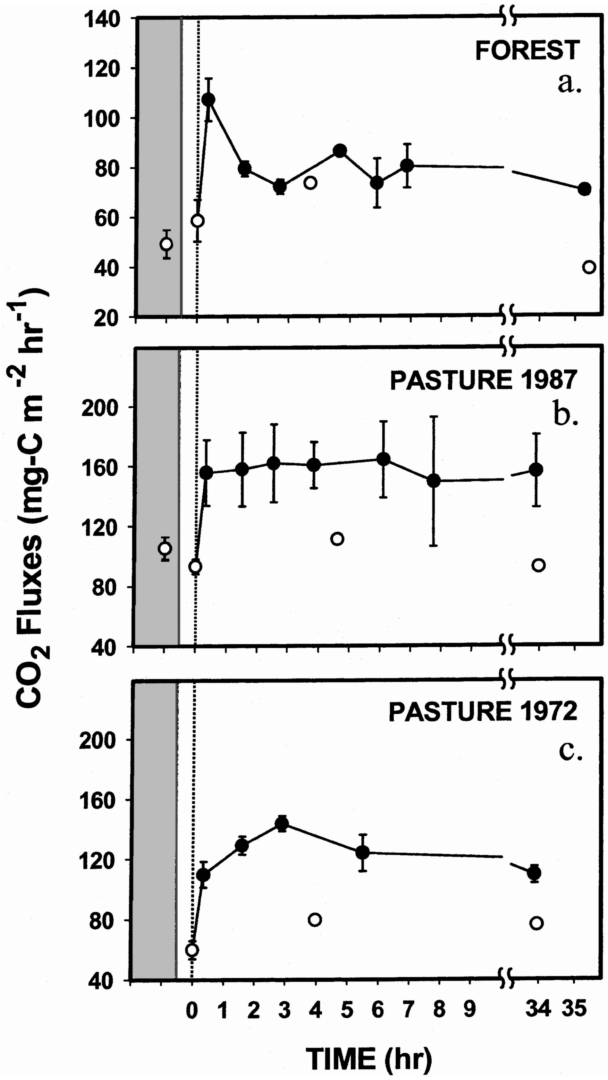

Figure 5. Fluxes of CO_2 during the irrigation experiment conducted in a forest (a) and 11- and 26-year-old pastures (b and c) at Nova Vida. Closed symbols represent CO_2 fluxes from irrigated plots and open symbols represent CO_2 fluxes from non-irrigated control plots. Shaded areas indicate measurements made the day before the irrigation experiment started and the vertical dashed line indicates when water was added to the soil. Error bars are standard errors.

Several hours after the end of the rain in forest, soil emissions of NO increased 2-fold relative to the pre-rain mean emissions (Figure 6a). In contrast, rain did not produce a large increase in forest N_2O emissions relative to the pre-rain emissions (Figure 6b). Pasture emissions of NO or N_2O showed very little change after the rain (Figure 6a and 6b).

Table 1. Mean (±SE) percent water-filled pore space (% WFPS) and NH_4^+ and NO_3^- pools during wet season, at the end of the dry season (n = 17) and right after 42.5 mm rain during 1998 in a forest and 11-year-old pasture at Nova Vida. Percent WFPS and N pools during the wet season (n = 32) were obtained from Garcia-Montiel et al. (2001). Measurements were done five times after the natural rain event. Error bars are standard errors.

	Soil Depth (cm)	% WFPS (μg N g^{-1} dry soil)	NH_4^+ Pools	NO_3^-Pools
Wet season				
Forest	0–5	36.1 ± 0.6	3.4 ± 1.2	4.2 ± 0.3
11-year-old Pasture	0–5	72.7 ± 1.5	6.8 ± 0.7	0.8 ± 0.1
End of dry season				
Forest	0–2	12.5 ± 1.2	14.6 ± 8.5	17.7 ± 3.1
	2–5	27.8 ± 0.2	0.8 ± 0.4	5.8 ± 0.3
	5–10	30.0 ± 0.7	2.8 ± 2.5	10.6 ± 3.5
11-year-old Pasture	0–2	14.9 ± 8.5	22.1 ± 8.5	0.5 ± 0.2
	2–5	36.6 ± 1.9	4.5 ± 1.2	0.3 ± 0.2
	5–10	24.5 ± 0.8	2.7 ± 0.3	0.3 ± 0.2
Natural rain event				
Forest	0–2	27.2 ± 1.1	20.0 ± 5.9	18.8 ± 4.5
	2–5	37.7 ± 2.1	4.0 ± 2.8	7.9 ± 1.1
	5–10	38.3 ± 1.0	0.2 ± 0.2	5.2 ± 0.3
11-year-old Pasture	0–2	26.2 ± 2.2	31.2 ± 6.17	0.7 ± 0.4
	2–5	83.5 ± 7.0	5.0 ± 1.6	0.1 ± 0.03
	5–10	34.0 ± 1.9	2.7 ± 0.8	0.1 ± 0.1

In the forest, end of dry season emissions of CO_2 were 65 mg N m^{-2} hr^{-1} (Figure 6c). In the pasture, this emission was 89 mg N m^{-2} hr^{-1}. Several hours after the rain in forest or pasture, CO_2 emissions increased only slightly relative to the pre-rain levels (Figure 6c).

Discussion

Few studies have estimated the magnitude of pulses of NO and N_2O emissions that may occur upon wetting the soil after prolonged dryness in tropical seasonal ecosystems, but the measurements that are available indicate that these gas pulses can make up a substantial proportion of the annual fluxes. For example, the simulation of 20 mm of rain in soils from a tropical deciduous forest in Mexico caused NO fluxes to increase by a factor of 100 (Davidson et al. 1991). Based on these results, Davidson et al. (1991) estimated that NO pulses from the first rain event could account for one third of the annual NO emissions from this dry tropical forest. The same wetting experiment also resulted in a large, but short-duration pulse of N_2O

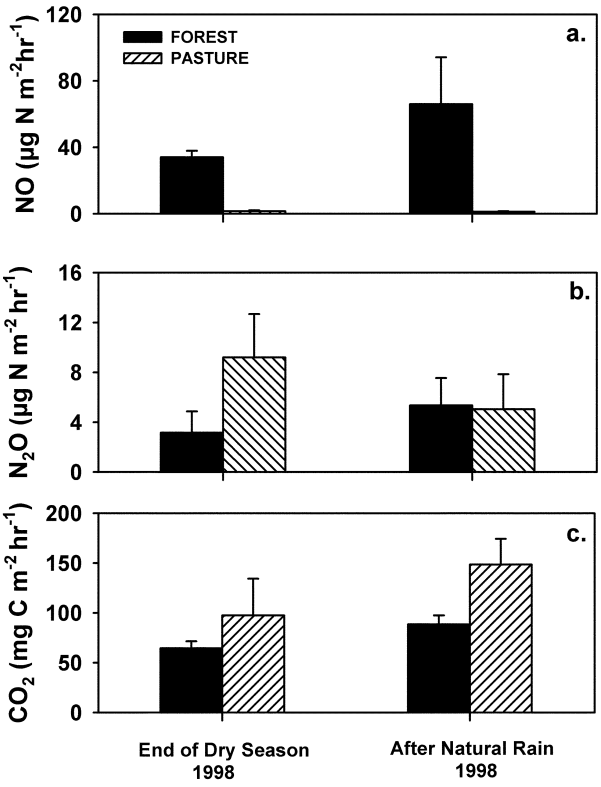

Figure 6. Fluxes of: a) NO, b) N_2O and c) CO_2 at the end of the dry season and after a 42.5 mm of rain during 1998 in a forest and 11-year-old pasture at Nova Vida. Average for the end of dry season fluxes of NO, N_2O and CO_2 are based on 17 individual measurements. Nitric oxide, N_2O and CO_2 fluxes were measured five times after the natural rain event. Error bars are standard errors.

that was estimated to account for less than 2% of the total annual emissions from this tropical dry forest soils (García-Méndez et al. 1991).

We estimated the amounts of the N oxides emitted from our wetting experiment by integrating the area between the curves of the irrigated and control plots (Figure 4). In the forest, wetting the soils produced a 0.24 mg N m^{-2} NO pulse and a 0.025 mg N m^2 N_2O pulse over the course of the experiment. Dry season emissions from this same forest averaged 35.8 μg N m^{-2} hr^{-1} of NO (n = 6; Garcia-Montiel et al. (2001) and Steudler et al. (2002)) and 13.6 μg N m^{-2} hr^{-1} of N_2O (n = 20; Melillo et al. (2001) and Garcia-Montiel et al. (2001), Steudler et al. (2002)). Multiplying these rates by the number of dry season days (153 days), we calculated a dry season emission of 131.4 mg N m^{-2} for NO and 50.1 mg N m^{-2} for N_2O. Based on these estimates, NO and N_2O released during the wetting experiment represented less than 0.2% of dry season emissions and even a smaller fraction of the annual emissions from the forest at Nova Vida.

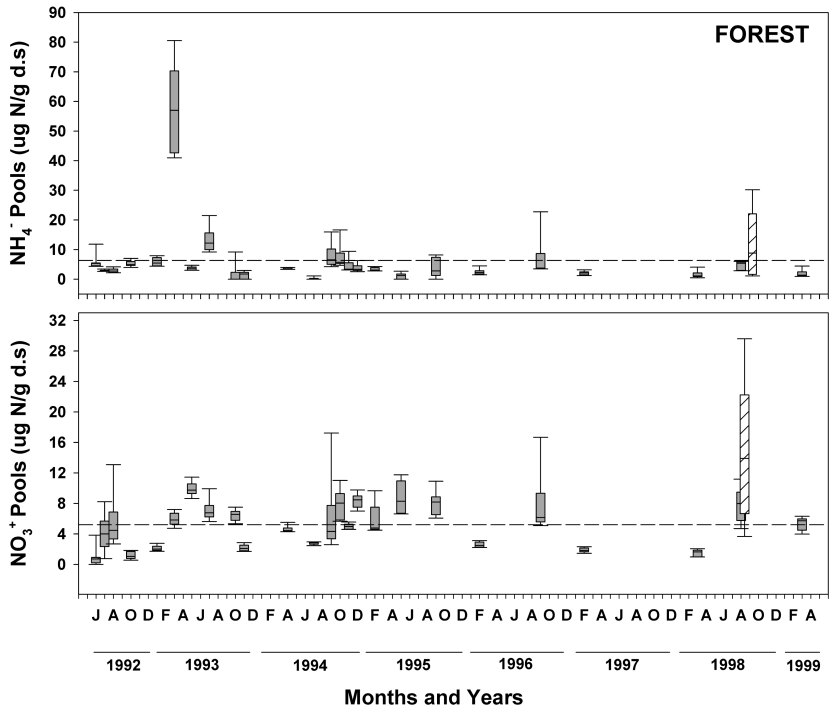

Figure 7. Long-term record (grey-filled boxes) of inorganic N pools (NH_4^+ and NO_3^-) from a forest at Nova Vida. Dashed boxes represent inorganic pools measured three days after the 17.2 mm rain event (August 10,1998) and at the start of the experiment (August 20,1998). The center horizontal line of the boxes represents the median. The hinges mark the first and third quantiles. The horizontal dashed line indicates the mean annual average for the NH_4^+ and NO_3^- pools.

We considered the possibility that the relatively small pulses we observed from the wetting experiment could be a consequence of the previous rain 10 or 12 days before the start of the experiment. This rain might have decreased soil N pools and thus reduced the N oxide pulses. However, data on N pools from soils collected between three days after the rain and right before the start of the experiment, indicated that the size of the NH_4^+ and NO_3^- pools were within the range of inorganic pools measured between 1992 and 1999 in the same forest and pasture soils (Figures 7 and 8).

To estimate the NO pulses from forest that resulted from the second rain, we used the time sequence of NO fluxes from the wetting experiment (Figure 4a) to proportion the NO emission of 66 μg N m^{-2} hr^{-1} (Figure 6a) that we measured 17 hours after the rain ended. We assumed that this pulse also returned to levels measured before the rain in less than 34 hours. This calculation resulted in a larger NO pulse of 1.5 mg N m^{-2} than measured from the wetting experiment.

At Nova Vida, the transition period from dry to wet season is coincident with a rainfall pattern frequently associated with the occurrence of individual rains delivering more than 17 mm of water and spaced by 15 or more days without rain. As-

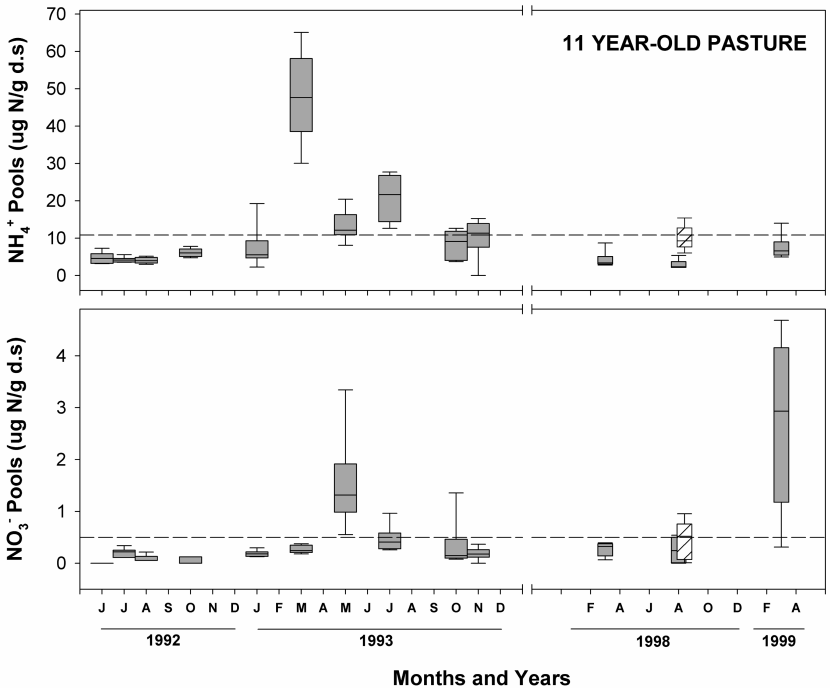

Figure 8. Long-term record (grey-filled boxes) of inorganic N pools (NH_4^+ and NO_3^-) from the 11-year-old pasture at Nova Vida. Dashed boxes represent inorganic pools measured three days after the 17.2 mm rain event (August 10,1998) and at the start of the experiment (August 18,1998). The center horizontal line of the boxes represents the median. The hinges mark the first and third quantiles. The horizontal dashed line indicates the mean annual average for the NH_4^+ and NO_3^- pools.

suming that during the transition period an average of three of these rain events occured (reflective of our long-term rain record over this period) and they all produce NO pulses of similar magnitude as those calculated from the second rain, we estimate a total pulse emission of 4.5 mg N m^{-2} over the transition period of about 6 weeks. Using the NO dry season emissions of 131.4 mg m^{-2}, we estimate that this pulse would represent 3.4% of the dry season emission and less than 2% of the annual NO emission (Figure 9).

Using the same procedure as for NO, we estimated that the N_2O pulse from the second rain was 0.3 mg N m^{-2} and the N_2O pulses resulting from a sequence of at least three rain events produced a total emission of 0.9 mg N m^{-2} during the transition period (Figure 9). This represents only 1.8% of the dry season N_2O emission of 50.1 mg N m^{-2} and less than 0.3% of the annual emission (Figure 9).

Pulses of N oxide emissions from pasture soils after the wetting experiment or the second rain event were even less important than in forest soils (Figures 4b, 4c and 6a,6b). Pulses of NO estimated from the pastures after irrigation or the increase observed after the second rain were both insignificant. Pulses of N_2O from the ir-

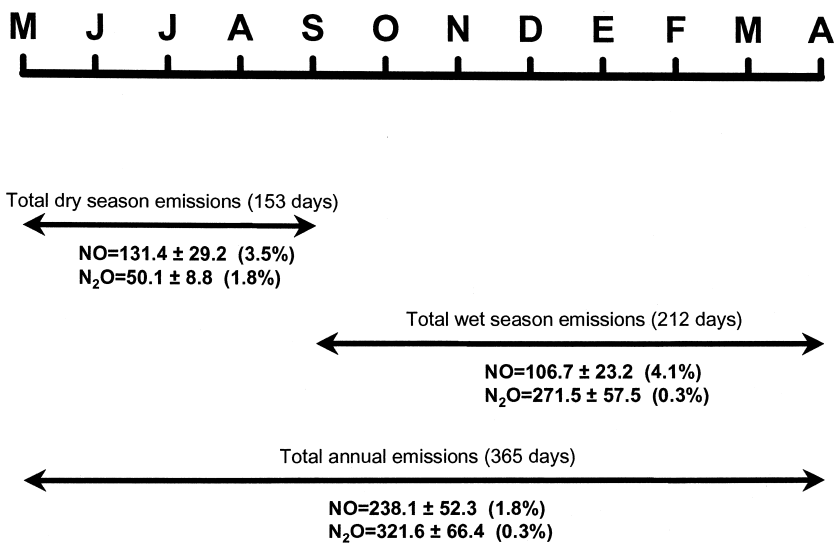

Figure 9. Pulses of NO and N_2O during the dry-wet transition period expressed as a percent (in parenthesis) of the dry and wet seasons and annual emissions. Seasonal emissions of NO and N_2O are expressed as mg N m^{-2}. Percent calculations used a transition period pulse of 4.5 mg N m^{-2} for NO and 0.9 mg N m^{-2} for N_2O. Dry season NO emissions (n = 6) were estimated from data collected during 1998 (Garcia-Montiel et al. 2001; Steudler et al. 2002). Dry season N_2O emissions (n = 20) were estimated from a long-term data set collected from 1992 through 1998 (Garcia-Montiel et al. 2001; Melillo et al. 2001; Steudler et al. 2002). Wet season emissions of NO (20.97+ 4.5 μg N/m^2/hunitr, n = 17) were estimated from a data set collected during 1998–1999 (Garcia-Montiel et al. 2001; Steudler et al. 2002). Wet season emissions of N2O (53.36 + 11.25 μg N/m^2/hunitr, n = 32) were estimated from a long-term data set collected from 1992 through 1999 (Garcia-Montiel et al. 2001; Melillo et al. 2001; Steudler et al. 2002).

rigation were only sizable in the 26-year-old pasture, however, this also represented a very small proportion of the dry season or annual emissions.

The pulses of N oxide emissions from forest soils were accompanied by rapid increases in CO_2 emissions. This large increase in CO_2 emissions immediately after irrigation suggests an increase in microbial metabolism acting on easily decomposable organic substrates, such as death microbial biomass, during immediate post wetting (Shields et al. 1974; Sørensen 1983). Laboratory incubations using ^{14}C-labeled substrates have demonstrated that upon soil wetting, soil microorganisms are capable of rapidly metabolizing readily decomposable substrates that originate from cells killed during the drying of the soils (Van Gestel et al. 1993). In pastures, although N oxide emissions following wetting were very small, CO_2 emissions increased. This indicates that there was an immediate increases in microbial activity upon wetting and suggests that the lack of N oxide fluxes was associated with the low N availability that characterizes pasture soils.

The severity and length of the dry season may explain the differences in the magnitude of the N oxide pulses observed between the dry deciduous Mexican forest (García-Méndez et al. 1991; Davidson et al. 1991) and the forest we examined

in Rondônia. The severe dry season that characterizes the forest at the Mexican site, where soils can dry to 2% water content, can produce a large effect on soil biomass and microbial activity. In the forest at Nova Vida, the soils are subject to a less severe dry season. The absence of drastic seasonal changes observed in the net rates of mineralization and nitrification measured in our forest (Neill et al. 1995) suggest a less severe effect on microbial activity.

In the forest, larger post-wetting emissions of NO over N_2O suggest that nitrification is the process that is triggered by the sudden increase in soil water availability. In the pastures, we observed larger post wetting emissions of N_2O over NO. Accumulations of NO_3^- at the end of the dry season do not occur in pasture soils; however, the sudden increase in % WFPS during the wetting experiment might create the anaerobic conditions that favor denitrification. Eventhough pasture post-wetting emissions of N_2O were larger than NO, pulses from both gases were low or insignificant, probably due to the low N availability that constrains N oxide emissions from these soils (Garcia-Montiel et al. 2001).

Annual forest NO and N_2O emissions

Based on our wet- and dry-season measurements from 1998–1999 (n = 23), we estimated that the forest soil at Nova Vida emitted about 2.38 kg NO-N/ha/yr (Figure 9). Our estimate is about 60% greater than the mean of 1.5 kg N/ha/yr reported by Davidson et al. (2001) for four mature Amazonian forests. It is not unexpected that there is variability among the estimates because the total number of studies is still quite limited.

We also estimated the annual N_2O emissions from this forest to be 3.21 kg N/ha which is greater than our previous estimate of 1.94 kg N/ha for the same forest (Melillo et al. 2001). The current estimate is based on a more extensive data set (n = 52) collected from 1992 through 1999 (Figure 9). One explanation for the differences in the estimates may be that the latest result captures more of the inter-annual variability in the fluxes. Nitrous oxide emissions are known to have high inter-annual variability (Prather and Ehhalt 2001). Davidson et al. (2001) compiled a data set of the annual N_2O emissions from mature Amazonian forests and reported a mean emission of 2.0 kg N/ha, about 62% less than we found.

Conclusions

Soil wetting after prolonged dryness produced very small pulses of NO or N_2O from forest soils and no significant pulses from pasture soils. From this study, we found no indication that forest conversion to pasture at Nova Vida creates the conditions necessary for increasing N oxide pulses. This study suggests that our estimates of seasonal and annual NO and N_2O fluxes from Rondônia have not missed an important component by not including these pulses. However, reformation and intensification of pastures and the use of fertilizer, especially those containing N,

will likely increase N oxide emissions from pastures because of increased N availability. As a consequence, the short-term dynamics associated with soil wetting after prolonged dryness could have a larger effect on the emissions of NO and N_2O to the atmosphere.

We found that the total N oxide emissions of 5.6 kg N/ha/yr from the forest were nearly evenly divided between NO (42%) and N_2O (58%). The emissions of NO were evenly distributed over the wet and dry seasons, while over 84% N_2O fluxes occurred during the wet season.

Acknowledgements

NASA provided founds for this study through the Terrestrial Ecology Program. We thank Sandra Nicolete, Keri Holland, and Suzanne Thomas for assistance. We also like to thank to João Arantes, Jr. and his family who generously allowed us to work on their land and to José Cardozo who provided logistical assistance.

References

Bastos T.X. and Diniz T.D.de A.S. 1982. Avaliação de clima do Estado de Rondônia para desenvolvimento agrícola. EMBRAPA-CPATU, Belém, Brazil, Boletim de Pesquisa 44.

Bowden R.D., Steudler P.A., Melillo J.M. and Aber J.D. 1990. Annual nitrous oxide fluxes from temperate forest soils in the northeastern United States. J. Geophys. Res 95: 13997–14005.

Breuer L., Papen H. and Butterbach-Bahl K. 2000. N_2O emission from tropical forest soils from Australia. J. Geophys. Res 105: 26353–26367.

Davidson E.A., Vitousek P.M., Matson P.A., Riley R., Garcia-Mendez G. and Maass J.M. 1991. Soil emissions of nitric oxide in a seasonally dry tropical forest of Mexico. J. Geophys. Res 96: 15439–15445.

Davidson E.A. 1992. Sources of nitric oxide and nitrous oxide following wetting of dry soil. Soil Sci. Soc. Am. J. 56: 95–102.

Davidson E.A., Matson P.A., Vitousek P.M., Riley R., Dunkin K., Garcia-Mendez G. et al. 1993. Processes regulating soil emissions of NO and N_2O in a seasonally dry forest. Ecology 74: 130–139.

Davidson E.A., Bustamante M.M.C. and de Siqueira Pinto A. 2001. Emissions of nitrous oxide from soils of native and exotic ecosystems of the Amaxon and Cerrado regions of Brazil. In: Optimizing Nitrogen Management in Food and Energy Production and Environmental Protection: Proceeding of the 2nd International Nitrogen Conference on Science and Policy. The Scientific World, pp. 312–319.

Feigl B.J., Steudler P.A. and Cerri C.C. 1995. Effects of pasture introduction on soil CO_2 emissions during the dry season in the State of Rondônia, Brazil. Biogeochemistry 31: 1–14.

García-Méndez G., Maass J.M., Matson P. and Vitousek P.M. 1991. Nitrogen transformations and nitrogen oxide flux in tropical deciduous forest in México. Oecologia 88: 362–366.

Garcia-Montiel D.C., Steudler P.A., Piccolo M.C., Melillo J., Neill C. and Cerri C.C. 2001. Controls on soil nitrogen oxide emissions from forest and pastures in the Amazon. Global Biochem. Cycles 15: 1021–1030.

Garcia-Montiel D.C., Neill C., Melillo J., Thomas S., Steudler P.A. and Cerri C.C. 2000. Soil phosphorus transformations following forest clearing for pasture in the Brazilian Amazon. Soil. Sci. Soc. Am. J. 64: 1792–1804.

de Graça P.M.L. 1997. Conteúdo de carbono na biomassa florestal da Amazônia e alterações após á queima. MS thesis, University of São Paulo, SP, Brazil.

Keller M. and Reiners W.A. 1994. Soil-atmosphere exchange of nitrous oxide, nitric oxide, and methane under secondary succession of pasture to forest in the Atlantic lowlands of Costa Rica. Global Biogeochem. Cycles 8: 399–409.

Melillo J., Steudler P.A., Feigl B.J., Neill C., Garcia-Montiel D.C., Piccolo M.C. et al. 2001. Nitrous oxide emissions from forest and pastures of various ages in the Brazilian Amazon. J. Geophys. Res. 24: 34,179–34,188.

Moraes J.F.L., Volkoff B., Cerri C.C. and Bernoux M. 1995. Soil properties under Amazon forest and changes due to pasture installation in Rondônia, Brazil. Geoderma 70: 63–81.

Neill C., Piccolo M.C., Steudler P.A., Melillo J.M., Feigl B.J. and Cerri C.C. 1995. Nitrogen dynamics in soils of forests and active pastures in the western Brazilian Amazon Basin. Soil Biol. Biochem 27: 1167–1175.

Neill C., Melillo J.M., Steudler P.A., Cerri C.C., Moraes J.F.L., Piccolo M.C. et al. 1997. Soil carbon and nitrogen stocks following forest clearing for pasture in the southwestern Brazilian Amazon. Ecol. Applic. 7: 1216–1225.

Piccolo M.C., Neill C. and Cerri C.C. 1994. Net nitrogen mineralization and nitrification along a tropical forest-to-pasture chronosequence. Plant and Soil 162: 61–70.

Prather M. and Ehhalt D. 2001. Atmospheric Chemistry and Greenhouse Gases. In: Houghton J.T. and Ding Y. (eds), Climate change 2001: The Scientific Basis. Cambridge University Press, Cambridge, UK, pp. 238–288.

Reiners W.A., Bouwman A.F., Parsons W.F.J. and Keller M. 1994. Tropical rain forest conversion to pasture: changes in vegetation and soil properties. Ecol. Appl. 4: 363–377.

Shields J.A., Paul E.A. and Lowe W.E. 1974. Factors influencing the stability of labelled microbial materials in soils. Soil Biol. Biochem. 6: 31–37.

Sørensen L.H. 1983. The influence of stress treatments on the microbial biomass and the rate of decomposition of humified matter in soils containing different amounts of clay. Plant and soil 75: 107–119.

Steudler P.A., Melillo J.M., Feigl B.J., Neill C., Piccolo M.C. and Cerri C.C. 1996. Consequence of forest-to-pasture conversion on CH_4 fluxes in the Brazilian Amazon Basin. J. Geophys. Res 101: 18547–18554.

Steudler P.A., Garcia-Montiel D.C., Piccolo M.C., Neill C., Melillo J.M., Feigl B.J. et al. 2002. Trace gas responses of tropical forest and pasture soils to N and P fertilization. Global Biochem. Cycles Vol. 16, No. 2, 10.1029/2001GB001394.

Unisearch Associates Inc. 1996. LMA-4 Operator's Manual. Concord, Ontario, Canada.

Van Gestel M.R., Merckx R. and Vlassak K. 1993. Microbial biomass responses to soil drying and rewetting: the fate of fast- and slow-growing microorganisms in soils from different climates. Soil Biol. Biochem. 25: 109–123.

Verchot L.V., Davidson E.A., Cattânio J.H., Ackerman I.L., Erickson H.E. and Keller M. 1999. Land use change and biogeochemical controls of nitroen oxide emissions from soils in eastern Amazonian. Global Biogeochem. Cycles 13: 31–46.