JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 101, NO. D13, PAGES 18,547–18,554, AUGUST 20, 1996

Consequence of forest-to-pasture conversion on CH_4 fluxes in the Brazilian Amazon Basin

Paul A. Steudler,[1] Jerry M. Melillo,[1] Brigitte J. Feigl,[2] Christopher Neill,[1] Marisa C. Piccolo,[2] and Carlos C. Cerri[2]

Abstract. Methane (CH_4) fluxes between soils and the atmosphere were measured in two tropical forest-to-pasture chronosequences in the state of Rondônia, Brazil. Forest soils always consumed atmospheric CH_4 with maximum uptake rates in the dry season. Pasture soils consumed atmospheric CH_4 during the dry season, but at lower rates than those in the forests. When soil moisture increased in the pasture soils, they became a source of CH_4 to the atmosphere. Integrated over the year, forest soils were a net sink of approximately 470 mg CH_4-C/m^2, while pastures were a net source of about 270 mg CH_4-C/m^2. Thus forest-to-pasture conversion resulted in a net source of CH_4 from the soil of about 1 g CH_4/m^2/yr. The total pasture-related CH_4 release for the entire Brazilian Amazon increased from 0.8 Tg CH_4 in 1970 to about 2.5 Tg CH_4 in 1990, with a maximum of 3.1 Tg CH_4/yr in 1988. Soils accounted for a small part (about 5%) of the total CH_4 release from the basin, while biomass burning and cattle emissions accounted for 95%. The average rate of increase in CH_4 emission from pastures was about 0.2 Tg CH_4/yr between 1975 and 1988. This represents between 12% and 14% of the global average rate of change in tropospheric CH_4 content for this time period.

Introduction

Methane (CH_4) is an important long-lived tropospheric gas that affects the chemical composition of the atmosphere. It decreases the concentration of hydroxyl radical and behaves as a radiatively active gas that can alter global surface temperatures [*Watson et al.*, 1990, 1992]. Methane contributes strongly to the atmospheric greenhouse effect, because CH_4 has combined direct and indirect total global warming potential that is about 25-60 times greater than CO_2 [*Albritton et al.*, 1995]. The abundance of CH_4 has been increasing in the tropospheric at an average rate of about 20 ppbv or 1.3%/yr during the late 1970s and at about 13 ppbv/yr or 0.8%/yr more recently during the late 1980s [*Khalil and Rasmussen*, 1994; *Prather et al.*, 1995]. The decrease in the rate of increase may be related to decreases in the rates of expansion of rice cultivation and cattle populations, two of the major CH_4 sources affected by human activities [*Khalil and Rasmussen*, 1994].

Globally, tropical ecosystems are considered to be important sources and sinks for CH_4. The major sources are primarily natural wetlands [*Bartlett and Harriss*, 1993] and human-influenced activities such as rice cultivation [*Shearer and Khalil*, 1993], domestic animals [*Anastasi and Simpson*, 1993], and biomass burning [*Andreae and Warneck*, 1994]. Upland forest and savanna soils are generally sinks for atmospheric CH_4 [*Keller et al.*, 1986, 1990; *Steudler et al.*, 1991; *Delmas et al.*, 1992a]. The conversion of natural forests to other land covers such as row crop agriculture or pasture appears to decrease the soil CH_4 sink [*Goreau and de Mello*, 1988; *Keller et al.*, 1990, 1993].

We examined the effects of forest conversion to pasture in the Brazilian Amazon. We focused our study in the Brazilian Amazon Basin because it has experienced very high rates of deforestation during the decade of 1980 to 1990 [*Instituto Nacional de Pesquisas Espaciais* (INPE), 1992; *Fearnside*, 1993; *Skole* et al., 1993, 1994]. For example, in the state of Rondônia, 34,200 km^2, or 16.1%, of the original forests had been cleared by 1991 [*INPE*, 1992; *Fearnside*, 1993]. Approximately 70% of cleared land was used as pasture for some period [*Serrão* 1992]. The principal objectives of the study were to develop (1) estimates of annual CH_4 consumption rates for intact open moist tropical forest soils, (2) annual estimates of CH_4 exchanges in two pasture chronosequences, (3) statistical relationships between environmental factors and CH_4 exchanges in forests and pastures, and (4) estimates of basinwide CH_4 emissions resulting from pasture creation and use.

[1]The Ecosystems Center, Marine Biological Laboratory, Woods Hole, Massachusetts.

[2]Centro de Energia Nuclear na Agricultura, University of São Paulo, Piracicaba, Brazil.

Paper number 96JD01551.
0148-0227/96/96JD-01551$09.00

Site Description

Over a 19-month period we made field measurements of greenhouse gases and soil chemistry at Fazenda Nova Vida, a 22,000-ha cattle ranch about 250 km south of Porto Velho along highway BR-364 (10°30'S, 62°30'W) in central Rondônia, Brazil. The climate is humid tropical with an annual mean precipitation of 2200 mm and a dry season from May to September [*Bastos*

and Diniz, 1982]. Annual mean temperature is 25.5°C with a seasonal variation of less than 5°C [*Bastos and Diniz*, 1982]. The predominant soil type at the Fazenda is a Tropudult (Podzólico Vermelho-Amarelo in the Brazilian classification) covered by open moist tropical forest with a large number of palms [*Pires and Prance*, 1986]. This soil type covers the largest area of the three major soil types within the Amazon Basin and represents about 22% of the total basin area [*Moraes et al.*, 1995].

Methods

Pastures were created by the slash and burn technique after selective removal of three to four economically important trees per hectare. No fertilizers or mechanized agricultural practices were used in any of the pastures. Two forest-to-pasture chronosequences were identified from ranch records and satellite images. Chronosequence I included a forest stand and pastures created directly from forest in 1989, 1987, 1983, 1979, 1972, 1951, and 1911. Chronosequence II was located about 10 km away and contained a forest stand and pastures cleared in 1989, 1987, and 1972. Pastures were planted with several introduced African grass species, *Brachiaria brizantha, B. humidicola, and Panicum maximum* [*Neill et al.*, 1995]. Cattle stocking rates varied between 1 and 1.5 animals per hectare over the course of the study.

Surface soil (0-10 cm) pH in the forests of both chronosequences was 4.9-5.0, but after conversion to pasture surface, soil pH reached a maximum of 7.1-6.3 in the 1987 pastures and remained above 5.5 for all the older pastures [Neill et al., 1995; Moraes et al., 1996]. Surface soil clay content was 16-29% at all sites. Forest soil bulk densities at 0-5 cm depth were 1.2 to 1.3 g/cm^3 in chronosequences I and II, respectively. Pasture bulk densities were greater than those in the forest and reached a maximum of 1.57 g/cm^3 in the 1983 pasture. The greatest changes in bulk density were measured in the 0-5 cm depth in the youngest pastures (1989 and 1987). A detailed description of the soil characteristics for the two chronosequences is given by *Neill et al.* [1995] and *Moraes et al.* [1996].

Methane flux measurements between the soil and the atmosphere were made at chronosequence I beginning in June 1992 and at chronosequence II beginning in July 1992 and continued through December 1993. Sampling dates were chosen to capture the annual pattern in precipitation. Methane fluxes were measured 3 times during the day at 0700, 1200, and 1700 hours, corresponding to minimum, maximum, and intermediate soil and air temperatures.

Methane fluxes were measured by using a two-part chamber design [*Bowden et al.*, 1990] with three chambers at each of the 12 sites. Chamber anchors were installed several days before the initial measurements were begun and remained in place throughout the study period. In each site, anchors were located about 6 m apart, and in the pastures, anchors were placed between clumps of tiller. Surface litter material was left in place, and there were no grass stems inside the anchors. Ambient air, 2.5, 5, and 10 cm soil temperatures were measured at one chamber at each site during each incubation. Chamber headspace gas samples were collected by using 20-mL nylon syringes [*Bowden et al.*, 1990) at the beginning of the incubation and at 5, 10, 20, or 30 min thereafter. Syringes were compressed to 15 mL to improve storage times. Laboratory storage experiments with subambient (0.501 ppmv) CH_4 showed that the concentration in the syringes increased by 3.1% after 7 days and 4.8% after 14 days. Experiments with superambient (4.08 ppmv) CH_4 showed a 0.87% decrease in concentration after 14 days. Gas samples were returned to the laboratory in Piracicaba, Brazil, and analyzed within 7 to 10 days. Methane concentrations were determined by using gas chromatography with a flame ionization detector [*Steudler et al.*, 1989]. Two Scott certified standards of 0.618 and 3.02 ppmv CH_4 in N_2 were used for calibration. Fluxes were calculated by using the linear change in CH_4 concentration with chamber incubation time.

Five soil cores were taken at each site for determination of gravimetric soil moisture at 0-5 cm and 5-10 cm depths once per day. Subsamples were taken from the same cores for determination of NH_4^+ and NO_3^- pools and net nitrogen mineralization and nitrification rates [*Neill et al.*, 1995]. Subsamples were also taken at the same depths for determination of particule density [*Blake and Hartge*, 1986].

Soil porosities were calculated for all sites in both chronosequences from soil bulk densities at 0-5 and 5-10 cm depths and the corresponding particle density data. We used the soil porosity information and soil moistures to calculate the percent water-filled pore space (%WFPS) at each site for every sampling date.

We used all the data collected in 1992 and 1993 to test for relationships between environmental variables and CH_4 fluxes. The effects of soil temperature, %WFPS, soil NH_4^+ and NO_3^- pools, net nitrogen mineralization, and nitrification rates on the fluxes of CH_4 were tested by using linear or multiple linear regression analysis (REG procedure of SAS, SAS Institute, Inc. 1987). We tested for differences in CH_4 fluxes at minimum or maximum soil temperature, using a one-way nonparametric analysis of variance and the Wilcoxon two-sample test analysis of variance (SAS). We used the same procedures to test for differences in %WFPS and CH_4 fluxes between the two forest stands. We estimated the annual CH_4 fluxes for the forest stands and pastures, using the average daily fluxes measured in 1993 by taking the mean rate from the six samplings and applying that rate over 365 days.

Results

Seasonal Temperature Variation

Mean daytime soil temperatures in the forest sites ranged from 20.5°C to 27.3°C for all depths, with the highest temperatures observed in October. Pasture soil temperatures were generally greater than those in the forests, and the oldest pastures (1951 and 1911) usually had the highest temperatures. Pasture soil temperatures at 2.5 cm depth ranged from 18.2°C to 32.9°C. The lowest temperatures were observed in July or August.

Daily Temperature Variation

Maximum daytime soil temperature was measured at a depth of 0-2.5 cm at all sites. Maximum soil temperatures in the forests generally occurred at 1200 hours. The greatest daily maximum-minimum difference of 4-5°C was measured in the dry season,

and the minimum difference of 1-2°C was measured during the wet season. Maximum daytime soil temperature in the pastures generally was measured at either 1200 or 1700 hours. The maximum daily difference of 12.5-16.0°C occurred during the dry season, and the minimum of 3-4°C occurred during the wet season. The 1972 and 1951 pastures showed the greatest variation in surface soil temperature.

Soil Moisture

Soil moistures at 0-5 and 5-10 cm depths in the forest stands ranged from 16% WFPS during the dry season to a maximum of 40% WFPS in March or May and were generally lower than in the pastures. Pasture soil moistures (0-5 cm) ranged from 7% to 73% WFPS during the dry and wet seasons. Soil moistures varied inversely with soil temperatures, so that the transition period from dry to wet season (September and October) had the highest temperatures but the lowest soil moistures.

Methane Exchanges

Forest soils always consumed atmospheric CH_4. The highest rates of up to 0.061 mg CH_4-C/m^2/h occurred in the dry season (Figure 1). Forest soil CH_4 consumption rates were 2 times lower during the wet season. Pasture soils showed CH_4 consumption during the dry season, but the uptake rates were lower than those in the forests (Figure 1). When soil moistures increased in the wet season, pasture soils were a source of CH_4 to the atmosphere of up to 0.52 mg CH_4-C/m^2/h. When integrated over the annual soil moisture cycle, most pastures were a net source of CH_4 to the atmosphere (Figure 2). Young pastures rapidly became net sources of CH_4. As early as 4 years after pasture establishment, annual CH_4 emissions were 202 to 122 mg CH_4-C/m^2 (Figure 2). Pasture emissions were variable but generally in the range of 50 to 300 mg CH_4-C/m^2. One pasture was a small net sink, and one was a large source (Figure 2).

Relationships Between Methane Exchanges and Environmental Variables

Soil temperature. Soil temperature was not an important factor controlling soil-to-atmosphere CH_4 exchanges. There were no significant differences ($p < 0.05$) between CH_4 fluxes at minimum or maximum soil temperatures for any of the individual forest stands or pasture sites or when all the forest or pasture sites were combined. There were no significant relationships between

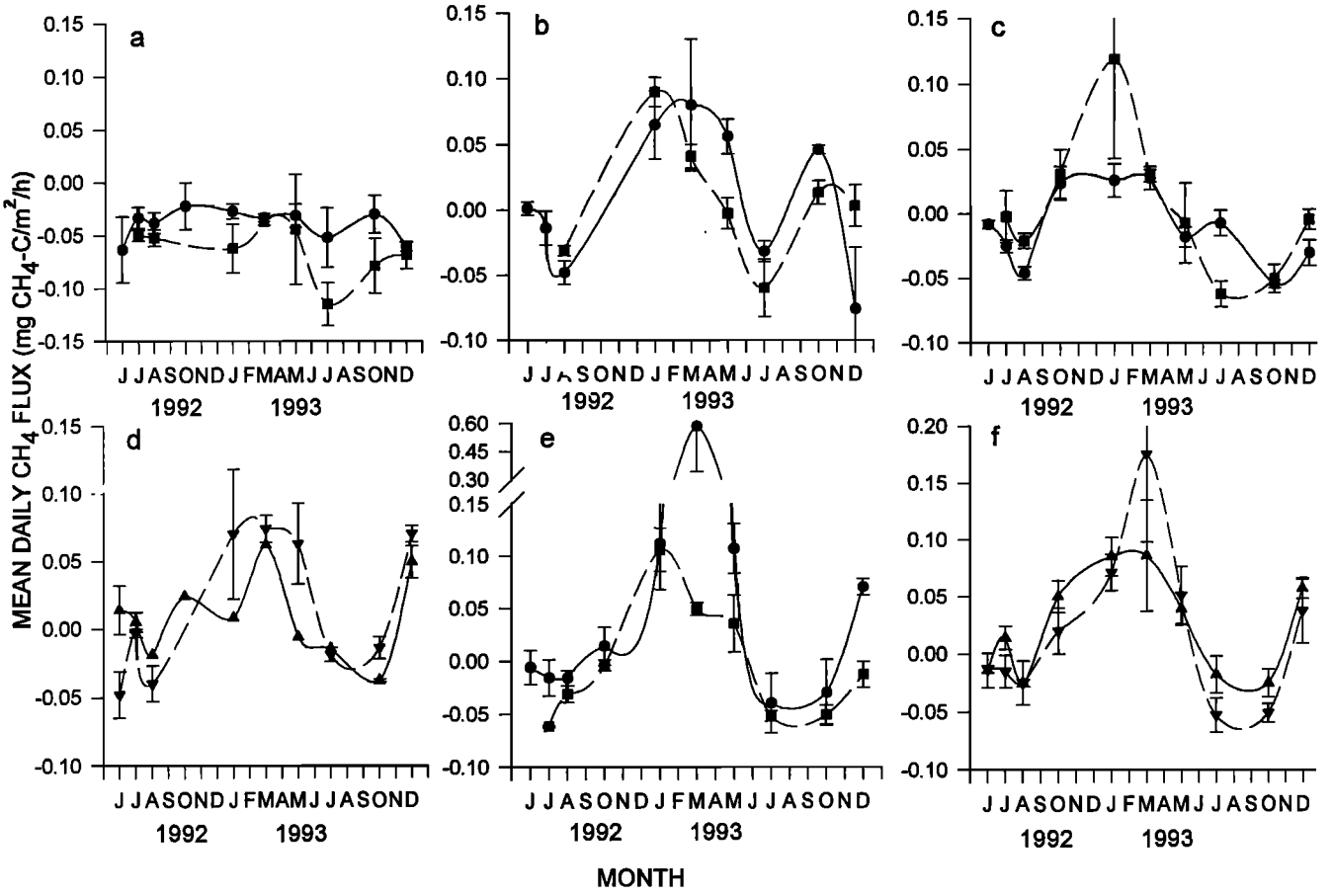

Figure 1. Mean daily soil CH_4 fluxes and standard errors (n=3) for chronosequences I (solid circles) and II (solid squares): (a) forest sites, (b) 1989 pastures, (c) 1987 pastures, (d) chronosequence I 1983 (triangles) and 1979 (inverted triangles) pastures, (e) 1972 pastures, (f) chronosequence I 1951 (triangles) and 1911 (inverted triangles) pastures. Positive fluxes are emissions to the atmosphere, and negative fluxes are soil consumption of atmospheric CH_4. Forest soils consumed atmospheric CH_4 with highest uptake rates during the dry season. Pasture soil CH_4 emissions typically peaked in December-March of each year.

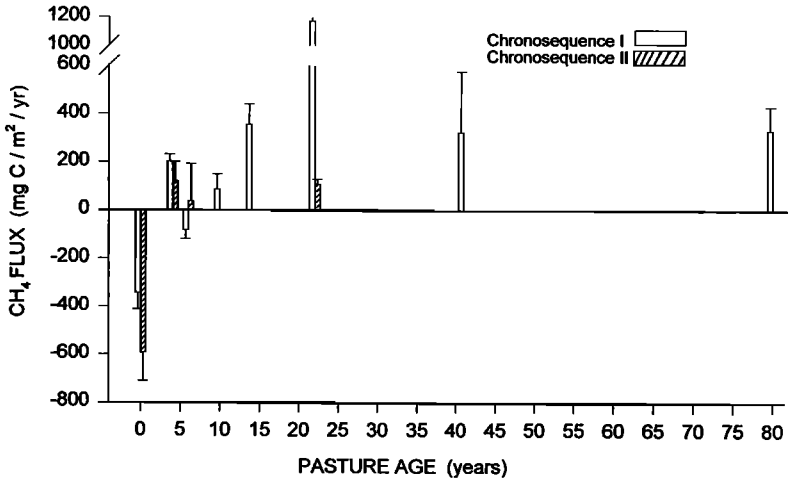

Figure 2. Annual mean CH_4 fluxes and standard errors (n=3) for the forest sites (0 age) and pastures of different ages from chronosequences I and II. Forest soils were a sink for atmospheric CH_4. Pasture soils were generally a net source of CH_4 to the atmosphere.

CH_4 fluxes and mean daytime temperatures over the sampling period (June 1992 through December 1993) in either the forest or pasture sites.

Soil moisture. We found that soil moisture was a strong predictor of CH_4 flux. Linear regression of CH_4 flux against %WFPS was highly significant ($p < 0.001$) and explained 52% of the variability in CH_4 flux when all the forest and pasture %WFPS at 0-5 cm depth data were combined and one outlier was removed (Figure 3). The outlier, chronosequence I pasture 1972 during the March 1993 sampling, was removed, because this pasture had unusually high CH_4 emissions (mean 0.58 mg CH_4-C/m^2/h) from two of the three chambers (0.18, 0.55, and 1.02 mg CH_4-C/m^2/h) compared to other pastures in chronosequence I and to the replicate 1972 pasture in chronosequence II (Figure 1). Multiple linear regression analysis was used to determine whether more of the variability in CH_4 fluxes could be explained by the addition of other parameters with %WFPS. We tested linear relationships between CH_4 flux against combinations of %WFPS and temperature, along with nitrogen pools or nitrogen dynamics. We found no substantial improvement in the predictive capability of the original relationship.

Discussion

Our result that %WFPS is a key factor controlling CH_4 exchange agrees with the relationship between CH_4 flux and effective diffusivity reported by *Keller and Reiners* [1994] for sites in Costa Rica. Percent WFPS is one important factor in determining whether a forest or pasture soil behaves as a source or sink of CH_4. At Nova Vida the range of 35-40% WFPS seems to be critical. Above 35-40%, soils behave as sources; below this range, soils behave as sinks. Pasture soils are compacted by cattle grazing, decreasing soil porosities, and limiting oxygen diffusion. Reduced soil aerobicity favors CH_4 production by methanogens, so that the net soil-atmosphere exchange is shifted to an emission when WFPS exceeds about 45%. Forest soils never exceed 40% WFPS, and this is one explanation of why they always consumed atmospheric CH_4. These results are consistent with the seasonal CH_4 fluxes reported by *Yavitt et al.* [1995] for organic rich soils in a temperate hardwood forest. They found net CH_4 emissions during spring field samplings when soil moistures were the greatest. Results from soil-air CH_4 profiles and laboratory incubations showed that CH_4 was produced in the organic layer when WFPS was around 70% or when the soils were made anaerobic.

Several other factors may contribute to why pastures generally are emitters of CH_4. The rate of methanogenesis is controlled by a number of parameters including pH, availability of competitive electron acceptors, and organic matter availability and quality [*Conrad*, 1989]. The creation of pastures at Nova Vida resulted in large changes in all these parameters.

The maximum rate of methanogenesis occurs at neutral pHs, although suboptimal rates have been measured in acidic soils [*Conrad*, 1989]. Forest surface soils at Nova Vida were acidic with pH values around 5, while the young pasture sites (1989 and 1987) had neutral pHs. Other pastures had pHs that were generally at least 1 unit greater than those in the forests. The effect of this large increase in pH in the pastures is to potentially enhance the rate of methanogenesis. For example, results from a laboratory study using an organic rich lake sediment showed that potential CH_4 production was increased by 20-fold when the pH was adjusted from 4 to 7 [*Valentine et al.*, 1994].

The availability of other electron acceptors such as SO_4^{-2} and NO_3^- also controls the rate of CH_4 production [*Conrad*, 1989]. *Tiedje* [1988] found that when more electronegative electron acceptors such as NO_3^- were available, other bacteria could successfully compete with fermenting and methogenic bacteria for carbon substrates, thereby reducing the rate of CH_4 production. Our forest stands have annual mean surface soil NO_3^- pools that are 4 to 7 times greater than those in the pastures [*Neill et al*, 1995]. Net nitrification rates were also 4 to 6 times greater in the forests compared to the pastures.

Carbon availability is another key factor influencing the rate of methanogenesis. Surface soil carbon stocks at Nova Vida generally increased in the pastures compared to the forest stands [*Feigl et al.*, 1995; *Neill et al.*, 1995; *Moraes et al*, 1996]. The degree of degradability of this available carbon influences the rate of CH_4 production [*Conrad*, 1989; *Valentine et al.*, 1994]. We have made measurements of various carbon fractions along

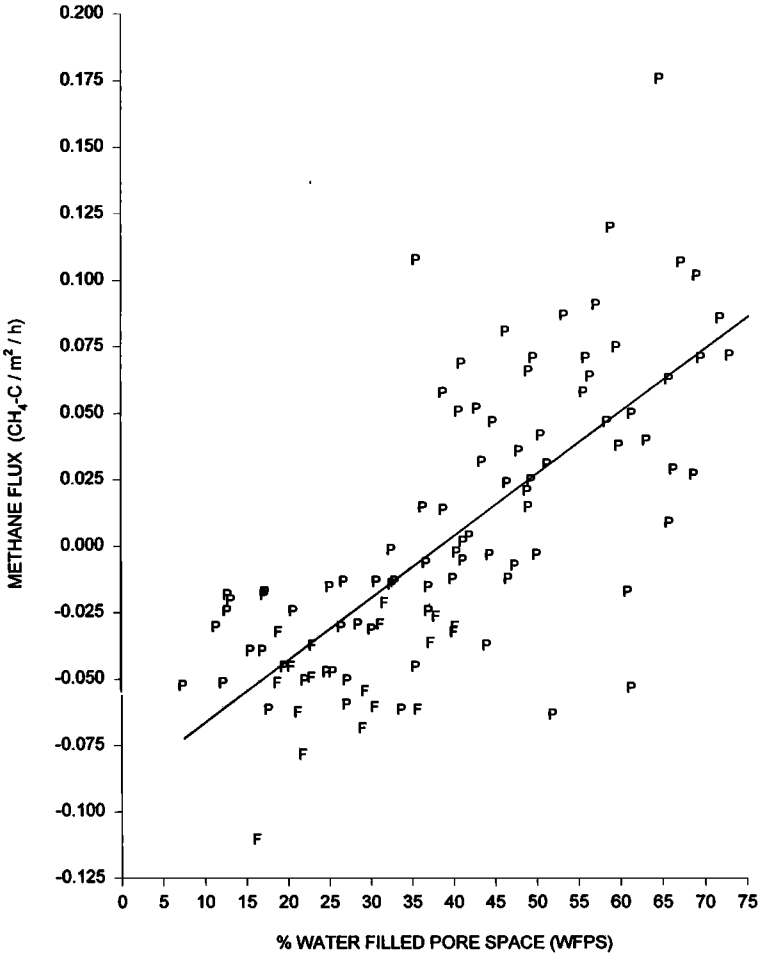

Figure 3. Mean daily CH_4 fluxes for all forest (F) and pasture (P) data from 1992 and 1993 (n=104) plotted against %WFPS at 0-5 cm depth. The linear regression equation is $y = -0.089 + 0.0023x$ (r^2=0.52).

chronosequence I, including cellulose concentrations, that indicate there was more labile carbon available to microbes in the pastures relative to the forest [*Feigl et al.*, 1995; B. J. Feigl, personal communication, 1995]. Our preliminary measurements indicate that cellulose concentrations were 8-50% higher in the pastures than in the forest. With our present knowledge we cannot evaluate the overall importance of each of these factors in the observed differences in the CH_4 fluxes between forest and pastures. However, it seems likely that because pastures have more optimal conditions for CH_4 production, the potential exists for higher emissions from the pastures than from the forests.

Chronosequence II forest soil always had significantly (p < 0.01) lower %WFPS at 0-5 cm depth than the forest in chronosequence I, possibly because chronosequence II forest had lower soil bulk density and greater soil porosity than the forest of chronosequence I. Since diffussion of atmospheric CH_4 into the soil is considered to be one of the most important controls of CH_4 consumption [*Born et al.*, 1990; *Striegl*, 1993], soils with greater soil porosity would be expected to have greater CH_4 uptake rates. This may be the reason why chronosequence II forest always had greater (p < 0.01) CH_4 uptake rates than chronosequence I forest (Figures 1 and 2).

Annual Flux Estimates

Where annual CH_4 fluxes have been measured in tropical forest soils, all have shown consumption with rates ranging from 149 to 530 mg CH_4-C/m^2 [*Keller et al.*, 1990; *Steudler et al.*, 1991; *Tathy et al.*, 1992; *Keller and Reiners*, 1994]. Methane consumption rates at Fazenda Nova Vida were from 342 to 593 mg CH_4-C/m^2/yr in the two forests sites. These rates are at the high end of the range but comparable to those measured by *Keller et al.* [1993] in two Costa Rican forests (335 mg CH_4-C/m^2) and to those measured by *Tathy et al.* [1992] in a central African wet forest (530 mg CH_4-C/m^2). The large variability in the rate of CH_4 consumption among these tropical forests may be primarily due to differences in the rate of CH_4 diffusion. However, we found in temperate forest sites that inherent site fertility as described by nitrogen turnover and differences in soil moisture regimes also may be important controlling factors in the rate of CH_4 oxidation [*Castro et al.*, 1995].

We calculated that on an annual basis, pastures were a net source of CH_4 to the atmosphere, ranging from 37 to 1172 mg CH_4-C/m^2 except for the 6-year-old (1987) pasture in chronosequence I, where a small uptake of 83 mg CH_4-C/m^2 was

measured (Figure 2). There are relatively few studies of the annual CH_4 fluxes for tropical pastures. *Keller et al.* [1990] measured a small annual uptake of about 55 mg CH_4-C/m^2 in a 15-year-old pasture in Panama, and *Keller and Reiners* [1994] found a mean emission of 58 mg CH_4-C/m^2 from three 30-year-old pastures in Costa Rica. For pastures with comparable ages we measured much larger emissions of 356 and 326 mg CH_4-C/m^2/yr in the 14- and 41-year-old pastures, respectively (Figure 2). *Keller et al.* [1993] reported a more extensive set of CH_4 flux measurements from two pasture chronosequences in Costa Rica. Their seasonally weighted annual estimate for all pastures combined was 177 mg CH_4-C/m^2 compared to our pasture mean of 271 mg CH_4-C/m^2. *Keller and Reiners* [1994] reported a pattern of decreasing CH_4 emissions in pastures greater than 5 years old for the pasture chronosequence at Guacimo, Costa Rica, but we did not see this in Brazil. Differences in grass tiller density and in pasture management regimes, including burning frequency and grazing pressure, may account for the different results of the two studies.

Using our mean annual forest CH_4 consumption rate of 468 mg CH_4-C/m^2 and a pasture mean of 271 mg CH_4-C/m^2, we estimate that conversion of tropical forests to pastures at Nova Vida results in a net emission of CH_4 to the atmosphere of 740 mg CH_4-C/m^2/yr. This estimate is about 44% greater than the emission from Costa Rican sites [*Keller et al.*, 1993]. Even if we use the higher ends of these rates for all tropical forests and pastures and the total area in tropical pastures is 2 times 10^6 km^2 [*Luizão et al.*, 1989], then globally, forest conversion to pasture results in a net emission of 2.0 Tg CH_4/yr. This is only a small fraction of the 535 Tg emitted annually from all sources [*Prather et al.*, 1995].

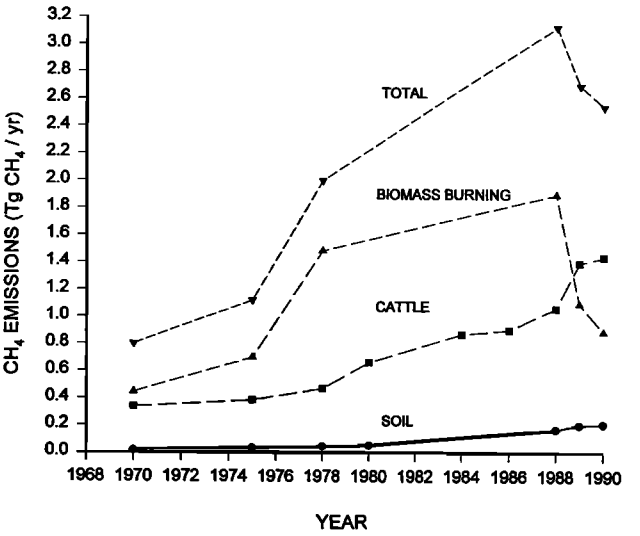

Figure 4. Estimates of the CH_4 emissions (Tg CH_4/yr) resulting from the conversion of natural forests-to-pastures and pasture operation in the Brazilian Amazon Basin for the period of 1970 through 1990. Total emissions rapidly increased from about 0.8 Tg CH_4/yr in 1970 to a maximum of 3.1Tg CH_4/yr in 1988. Biomass burning and cattle emissions were the dominant sources (95%) of CH_4 released from the basin.

Basinwide Flux Estimates

To compare soil emissions with total CH_4 releases caused by deforestation, we estimated the total CH_4 emissions associated with forest-to-pasture conversion and pasture operations in the legal Amazon Basin. Basinwide soil CH_4 emissions were calculated by extrapolating our soil fluxes, using the deforested areas reported by *INPE* [1992], *Fearnside* [1993], *Skole and Tucker* [1993] and *Skole et al.* [1994]. The areas and rates we used are for deforestation of natural forests and do not include savanna clearing. We adjusted the deforested areas reported by INPE and Fearnside to exclude the areas that already existed as secondary vegetation before 1970. We assumed that 70% of the deforested areas were converted into pasture [*Serrão*, 1992]. Basinwide soil CH_4 emissions were about 0.02 Tg in 1970 but increased more than 10-fold to 0.22 Tg by 1990 (Figure 4). While the change in soil emissions over the period was quite large, the magnitude of the release was small compared to other sources related to forest clearing.

Several additional CH_4 sources associated with pasture introduction and use include termites, cattle, and releases from biomass burning. Because we lacked quantitative information on the change in the abundance of wood-, fungus-, and soil-feeding termite nests in pastures compared to the original forest, a complete analysis of the contribution from termites was not possible. However, we can place an upper limit on potential CH_4 emissions from termites in pastures by assuming that the original forests had no termite-related CH_4 emissions. *Delmas et al.* [1992b] found CH_4-C/CO_2-C flux ratios from termite mounds in an equatorial forest in Africa similar to the releases measured in other tropical forests [*Goreau and de Mello*, 1998; *Khalil et al.*, 1990; *Martius et al.*, 1993] and in African savannas [*Seiler et al.*, 1984]. On the basis of species-specific CH_4 emissions and the areal distributions of soil- (85%) and wood-feeding termite mounds, *Delmas et al.* [1992b] estimated that termites emitted about 0.11 mg CH_4/m^2/d. If we assume that the areal emission rate reported by Delmas et al. is representative for the pastures at Nova Vida, then the CH_4 emissions from termites in pastures is about 10 times less than our average pasture emission of approximately 1 mg CH_4/m^2/d. *Bandeira and Torres* [1985] measured the biomass of wood- and soil-feeding termites in a primary forest and a 10-year-old pasture in Pará and found that the biomass in the pasture was more than seven-fold less than in the forest. We recognize that this is a preliminary analysis of the contribution of CH_4 from termites but there would have to be a substantial increase in termite biomass in very young pastures compared to the original forest for the emission from termites to be more than a minor source. Our conclusion is similar to that reached by *Delmas et al.* [1992a], in Africa where they also found termites to be only a minor source.

We computed the CH_4 emitted from cattle, using an annual emission rate of 55 kg CH_4 per head for range-grazing cattle [*Crutzen et al.*, 1986; *Lerner et al.* 1988; *Anastasi and Simpson*, 1993] and Brazilian government annual cattle population statistics for 1970 through 1990 [Instituto Brasileiro de Geografia e Estatistica, 1972-1993]. We used only the cattle statistics from the nine states that comprise the legal Amazon Basin. Methane releases from cattle increased from 0.34 Tg in 1970 to more than 1.4 Tg by 1990 (Figure 4). They were more than six-fold greater than the corresponding soil emissions.

We estimated the release of CH_4 from biomass burning, using an average of 17.17 kg C/m^2 for total preburn above ground forest carbon and a combustion efficiency of 50% [*Kauffman et al.* 1995]. These measurements were made in four primary forest

sites in the states of Rondônia and Pará which are located in the regions with the highest clearing rates. These estimates are similar to measurements made by *Ward et al.* [1992] for another primary forest in Pará but are greater than those estimated by *Fearnside et al.* [1993] in a forest near Manaus. The rate of deforestation was calculated by using the data presented by *Skole and Tucker* [1993] for 1970 and 1975 and by *INPE* [1992], *Fearnside* [1993] and *Skole et al.* [1994] for the remaining years. We adjusted these rates to reflect that 70% of clearing was converted to pasture. We calculated the emissions assuming that 90% of the carbon is converted to CO_2 with a $C\text{-}CH_4/C\text{-}CO_2$ emission ratio of 1.1% [*Levine et al.*, 1993; *Andreae and Warneck*, 1994]. Biomass burning was the dominant source of CH_4 during the period 1978 through 1988 but declined sharply in the late 1980s (Figure 4). In 1988, biomass burning and cattle emissions accounted for 95% of the total basinwide release of 3.1 Tg.

We can assess the effect of increased CH_4 emissions due to pasture introduction in the Amazon Basin on the global CH_4 budget by calculating the average annual increase between 1975 and 1988 (Figure 4). This increase was about 0.2 Tg CH_4/yr over the period. This represents between 12% and 14% of the average rate of change in the global emissions of 1.4 to 1.6 Tg CH_4/yr over the period 1978-1990 [*Steele et al.*, 1992; *Khalil and Rasmussen*, 1993]. This analysis assumes that tropospheric OH concentration was constant during the period. Recently, *Prinn et al.* [1995] used an analysis of the atmospheric trends and lifetime of CH_3CCl_3 to deduce that tropospheric OH concentrations showed little change ($0.0 \pm 0.2\%$/yr) from 1978 to 1994. Thus our analysis suggests that pasture introduction in the Amazon Basin may have been an important contributor to the increase in the atmospheric burden over this time. Future CH_4 emissions associated with cattle ranching in the basin are difficult to predict because of uncertainty in governmental economic incentives for pasture development and market demand for beef cattle. If deforestation in the Brazilian Amazon continues at the 1990 rate and cattle populations remain constant, then CH_4 emissions may stabilize at about 2.5 Tg/yr from this region.

Conclusions

Clearing forests for pasture agriculture altered the soil-atmosphere exchanges of CH_4 from a sink in forests to a net source in pastures. Soils accounted for a small part (about 5%) of the basin's total CH_4 release associated with pasture establishment and use, while biomass burning and cattle emissions accounted for 95%. The basinwide increase in CH_4 emissions associated with pasture introduction may have accounted for 14% of the global average annual increase in tropospheric CH_4 during the 1980s. At the end of the 1980s, changes in Brazilian government policies resulted in a decrease in the rate of forest clearing for pasture development. It is clear that government policies can affect CH_4 emissions from pasture creation and operation in the basin.

Acknowledgments. Funding for this research was provided by grants from the National Aeronautics and Space Administration, the Texaco Foundation, and the Conservation Food and Health Foundation Inc. to the Marine Biological Laboratory, Woods Hole, Massachusetts. The authors thank Gilmar Dri and Arildo Lopez for their assistance with the fieldwork, Sandra Nicoletti and Martial Bernoux with the laboratory analyses, João Arantes Jr. for permission to work at Fazenda Nova Vida, and José Cardozo for his support at Nova Vida. We thank João Luis Esteves (INCRA-RO), Emater-RO, EMBRAPA-RO, and the Secretary of Agriculture, Rondônia, for their valuable logistical support. This study is a product of the cooperative research activity, Floresta-Pastagem-Brasil; a joint research program between Carlos C. Cerri at the Centro de Energia Nuclear na Agricultura (CENA), University of São Paulo, and The Ecosystems Center at the Marine Biological Laboratory.

References

Albritton, D. L., R. G. Derwent, I. S. A. Isaksen, M. Lal, and D. J. Wuebbles, Trace gas radiative forcing indices, in *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios*, edited by J. T. Houghton et al., pp. 206-231, Cambridge Univ. Press, New York, 1995.

Anastasi, C., and V. J. Simpson, Future methane emission from animals, *J. Geophys. Res.*, *98*, 7181-7186, 1993.

Andreae, M. O., and P. Warneck, Global methane emissions from biomass burning and comparison with other sources, *Pure Appl. Chem.*, *66*, 162-169, 1994.

Bandeira, A. G., and M. F. P. Torres, Abundância e distribuição de invertebrados do solo em ecossistemas da Amazônia Oriental: O papel ecológico dos cupins, *Bol. Mus. Pará Emílio Goeldi Zool. 2*, 13-38, 1985.

Bartlett, K. B., and R. C. Harriss, Review and assessment of methane emission from wetlands, *Chemosphere*, *26*, 261-320, 1993.

Bastos, T. X., and T. D. de A. S. Diniz, Avaliação do clima do Estado de Rondônia para desenvolvimento agrícola, *Bol. Pesqui.* EMBRAPA-CPATU, no. 44, 1982.

Blake, G. R., and K. H. Hartge, Particle density, *in Methods of Soil Analysis. Physical and Mineralogical Methods*, edited by A. Klute, pp. 377-381, Am. Soc. Agron., Madison, Wis., 1986.

Born, M., H. Dorr, and I. Levin, Methane consumption in aerated soils of the temperate zone, *Tellus*, *42B*, 2-8, 1990.

Bowden, R. D., P. A. Steudler, J. M. Melillo, and J. D. Aber, Annual nitrous oxide fluxes from temperate forest soils in the northeastern United States, *J. Geophys. Res.*, *95*, 13,997-14,005, 1990.

Castro, M. S., P. A. Steudler, J. M. Melillo, J. D. Aber, and R. D. Bowden, Factors controlling atmospheric methane consumption by temperate forest soils, *Global Biogeochem. Cycles*, *9*, 1-10, 1995.

Conrad, R., Control of methane production in terrestrial ecosystems, in Exchange of Trace Gases Between Terrestrial Ecosystems and the Atmosphere, edited by M. O. Andreae and D. S. Schmil, pp. 39-58, John Wiley, New York, 1989.

Crutzen , P. J., I. Aselmann, and W. Seiler, Methane production by domestic animals, wild ruminants, and other herbivorous fauna, and humans, *Tellus*, *38B*, 271-284, 1986.

Delmas, R. A., J. P. Tathy, and B. Cross, Atmospheric methane budget in Africa, *J. Atmos. Chem.*, *14*, 395-409, 1992a.

Delmas, R. A., J. Servant, J. P. Tathy, B. Cross, and M. Labat, Sources and sinks of methane and carbon dioxide exchanges in mountain forest in equatorial Africa, *J. Geophys. Res.*, *97*, 6169-6179, 1992b.

Fearnside, P. M., Deforestation in Brazilian Amazonia: The effect of population and land tenure, *Ambio*, *22*, 537-545, 1993.

Fearnside, P. M., N. Leal Jr., and F. M. Fernandes, Rainforest burning and the global carbon budget: Biomass, combustion efficiency, and charcoal formation in the Brazilian Amazon, *J. Geophys. Res.*, *98*, 16,733-16,743, 1993.

Feigl, B. J., J. M. Melillo, and C. C. Cerri, Changes in the origin and quality of soil organic matter after pasture introduction in Rondônia (Brazil), *Plant Soil*, *174*, 21-29, 1995.

Goreau, T. J., and W. Z. de Mello, Tropical deforestation: Some effects on atmospheric chemistry, *Ambio*, *17*, 275-281, 1988.

Instituto Brasileiro de Geografia e Estatistica, *Censo Agropecuário*, Rio de Janeiro, Brazil, 1972-1993.

Instituto Nacional de Pesquisas Espaciais (INPE), *Deforestation in Brazilian Amazonia*, São Paulo, Brazil, 1992.

Kauffman, J. B., D. L. Cummings, D. E. Ward, and R. Babbitt, Fire in the Brazilian Amazon: Biomass, nutrient pools, and losses in slashed primary forests, *Oecologia*, *104*, 397-408, 1995.

Keller, M., and W. A. Reiners, 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, 1994.

Keller, M., W. A. Kaplan, and S. C. Wofsy, Emissions of N_2O, CH_4, and CO_2 from tropical forest soils, *J. Geophys. Res., 91*, 11,791-11,802, 1986.

Keller, M., M. E. Mitre, and R. F. Stallard, Consumption of atmospheric methane in soils of Central Panama: Effects of agricultural development, *Global Biogeochem. Cycles, 4*, 21-27, 1990.

Keller, M., E. Veldkamp, A. M. Weitz, and W. A. Reiners, Effect of pasture age on soil trace-gas emissions from a deforested area of Costa Rica, *Nature, 365*, 244-246, 1993.

Khalil, M. A. K., and R. A. Rasmussen, Decreasing trend of methane: Unpredictability of future concentrations, *Chemosphere, 26*, 803-814, 1993.

Khalil, M. A. K., and R. A. Rasmussen, Trends of atmospheric methane, *Pure Appl. Chem., 66*, 143-147, 1994.

Khalil, M. A. K., R. A. Rasmussen, J. R. J. French, and J. A. Holt, The influence of termites on atmospheric trace gases: CH_4, CO_2, $CHCl_3$, N_2O, CO, H_2, and light hydrocarbons, *J. Geophys. Res., 95*, 3619-3634, 1990.

Lerner, J, E. Matthews, and I. Fung, Methane emission from animals: A global high-resolution data base, *Global Biogeochem. Cycles, 2*, 139-156, 1988.

Levine, J. S., W. R. Cofer III, and J. P. Pinto, Biomass Burning, in *Atmospheric Methane: Sources, Sinks, and Role in Global Change*, edited by M. A. K. Khalil, pp. 299-313, Springer-Verlag, New York, 1993.

Luizão, F., P. Matson, G. Livingston, R. Luizão, and P. Vitousek, Nitrous oxide flux following tropical land clearing, *Global Biogeochem. Cycles, 3*, 281-285, 1989.

Martius, C., R. Wassmann, U. Thein, A. Bandeira, H. Rennenberg, W. Junk, and W. Seiler, Methane emission from wood-feeding termites in Amazonia, *Chemosphere, 26*, 623-632, 1993.

Moraes, J. F. L., C. C. Cerri, J. M. Melillo, D. Kicklighter, C. Neill, D. Skole, and P. Steudler, Soil carbon stocks of the Brazilian Amazon basin, *Soil Sci. Soc. Am. J., 59*, 244-247, 1995.

Moraes, J. F. L., B. Volkoff, C. C. Cerri, and M. Bernoux, Soil properties under Amazon forest and changes due to pasture installation in Rondônia/Brazil, *Geoderma, 70*, 63-81, 1996.

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

Pires, J. M., and G. T Prance, The vegetation types of the Brazilian Amazon, in *Key Environments: Amazonia*, edited by G. T. Prance and T. M. Lovejoy, pp. 109-129, Pergamon, Tarrytown, N.Y., 1986.

Prather, M., R. Derwent, D. Ehhalt, P. Fraser, E. Sanhueza, and X. Zhou, Other trace gases and atmospheric chemistry, in *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios*, edited by J. T. Houghton, et al., pp. 74-126, Cambridge Univ. Press, New York, 1995.

Prinn, R. G., R. F. Weiss, B. R. Miller, J. Huang, F. N. Alyea, D. M. Cunnold, P. J. Fraser, D. E. Hartley, and P. G. Simmonds, Atmospheric trends and lifetime of CH_3CCl_3 and global OH concentrations, *Science, 269*, 187-192, 1995.

Seiler W., R. Conrad, and D. Scharffe, Field studies of methane emission from termite nests into the atmosphere and measurements of methane uptake by tropical soils, *J. Atmos. Chem., 1*, 171-186, 1984.

Serrão, E. A., Alternative models for sustainable cattle ranching on already deforested lands in the Amazon, *An. Acad. Bras. Cien., 97*-104, 1992.

Shearer, M. J., and M. A. K. Khalil, Rice agriculture: Emissions, in *Atmospheric Methane: Sources, Sinks, and Role in Global Change*, edited by M. A. K. Khalil, pp 230-253, Springer-Verlag, New York, 1993.

Skole, D., and C. Tucker, Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1978 to 1988, *Science, 260*, 1905-1910, 1993.

Skole, D. L., W. H. Chomentowksi, W. A. Salas, and A. D. Nobre, Physical and human dimensions of deforestation in Amazonia, *BioScience 44*, 314-322, 1994.

Steele, L. P., E. J. Dlugokencky, P. M. Lang, P. P. Tans, R. C. Martin, and K. A. Masarie, Slowing down of the global accumulation of atmospheric methane during the 1980's, *Nature, 358*, 313-316, 1992.

Steudler, P. A., J. M. Melillo, R. D. Bowden, and J. D. Aber, Influence of nitrogen fertilization on methane uptake in temperate forest soils, *Nature, 341*, 314-316, 1989

Steudler, P. A., J. M. Melillo, R. D. Bowden, M. S. Castro, and A. E. Lugo, The effects of natural and human disturbances on soil nitrogen dynamics and trace gas fluxes in Puerto Rican wet forest, *Biotropica 23*, 356-363, 1991.

Striegl, R. G., Diffusion limits for the consumption of atmospheric methane by soils, *Chemosphere 26* (1-4), 715-720, 1993.

Tathy, J. P., B. Cros, R. A. Delmas, A. Marenco, J. Servant, and M. Labat, Methane emission from flooded forest in Central Africa, *J. Geophys. Res., 97*, 6159-6168.

Tiedje, J. M., Ecology of denitrification and dissimilatory nitrate reduction to ammonium, in *Biology of Anaerobic Microorganisms*, edited by A. J. B. Zehnder, pp. 179-244, John Wiley, New York, 1988

Valentine, D. W., E. A. Holland, and D. S. Schimel, Ecosystem and physiological controls over methane production in norther wetlands, *J. Geophys. Res., 99*, 1563-1571, 1994.

Ward, D. E., R. A. Susott, J. B. Kauffman, R. E. Babbitt, D. L. Cummings, B. Dias, B. N. Holben, Y. J. Kaufman, R. A. Rasmussen, and A. W. Setzer, Smoke and fire characteristics for Cerrado and deforestation burns in Brazil: Base-B experiment, *J. Geophys. Res., 97*, 14,601-14,619, 1992.

Watson, R. T., H. Rodhe, H. Oeschger, and U. Siegenthaler, Greenhouse gases and aerosols, in *Climate Change: The IPCC Scientific Assessment*, edited by J. T. Houghton, G. J. Jenkins, and J. J. Ephraums, pp. 1-40, Cambridge Univ. Press, New York, 1990.

Watson, R. T., F. Meira, E. Sanhuez, and A. Janetos, Greenhouse gases: Sources and sinks and aerosols, in *Climate Change 1992: The Supplementary Report to The IPCC Scientific Assessment*, edited by J. T. Houghton, B. A. Callander, and S. K. Varney, pp. 25-46, Cambridge Univ. Press, New York, 1992.

Yavitt, J. B., T. J. Fahey, and J. A. Simmons, Methane and carbon dioxide dynamics in a northern hardwood ecosystem, *Soil Sci. Soc. Am. J., 59*, 796-804, 1995.

C. C. Cerri, B. J. Feigl, and M. C. Piccolo, Centro de Energia Nuclear na Agricultura, University of São Paulo, CP 96, 13416-000 Piracicaba, SP, Brazil.

J. M. Melillo, C. Neill, and P. A. Steudler (corresponding author), The Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA 02543. (e-mail: steudler@lupine.mbl.edu)

(Received September 22, 1995; revised February 29, 1996; accepted February 29, 1996.)