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EDITORS:
Diva Athié - International Atomic Energy Agency Project BRA/0/010
Thomas E. Lovejoy - World Wildlife Fund-US
Pieter de Marez Oyens - World Wildlife Fund-US

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ORGANIZING COMMITTEE:

Diva Athié
International Atomic Energy Agency Projects-CENA

Thomas E. Lovejoy
World Wildlife Fund-US

Pieter de Marez Oyens
World Wildlife Fund-US

Frederico M. Wiendl
Centro de Energia Nuclear na Agricultura

PROGRAMME COMMITTEE:

Thomas E. Lovejoy
World Wildlife Fund-US

Peter B. Vose
Consultant-IAEA

Eneas Salati
Scientific Advisor

Preface

The biogeochemistry of tropical forests is an important scientific challenge in two ways, namely their internal cycles and their role in global processes.

The frequent failure to convert tropical forest to sustainably productive agricultural land is in many senses a problem of biogeochemistry. What is it about tropical forests that enables such highly diverse systems to exist in some instances on top of some of the poorest soils on earth? At the same time what is it about deforestation that allows only a temporary pulse of productivity? The answer lies in nutrient cycling in the intact burned forest, and a pulse of nutrients made available by the ashes of burned forest. But the details, and what they suggest about ways to use tropical forests sustainably are only known sketchily. Biogeochemistry has a lot to contribute to our understanding of how to save the great equatorial forests through intelligent use, as well as ways in which to recuperate already degraded land.

The great tropical forests, forming a major portion of the world's biomass, may have very important roles beyond their immediate neighborhood through global cycling of elements, energy and water. With rapid deforestation of about 72,000 km^2/year, these roles may be changing. In attempting to maintain a stable planetary environment and atmosphere, the part played by tropical forests needs clear definition.

The tropical forests represent, of course, far more than major pools and fluxes of elements, energy and water. If recent studies of beetles in the forest canopy of Amazonia are borne out by further work, the diversity of these forests is greater than anyone has ever appreciated, and more than three quarters of all forms of life are crowded into this 6-7% of the land surface of the planet.

These also must be, by orders of magnitude, the most complex systems known in the universe. As science reveals the extent of biological diversity in the tropical forests, the need to understand biogeochemistry on the level of the individual forest and the globe, and to use that knowledge to safeguard this amazing pool of resources gains even greater importance.

Brazil's Center for Nuclear Energy in Agriculture (Centro de Energia Nuclear na Agricultura - CENA) and the World Wildlife Fund (WWF) planned this Workshop to stimulate research on biogeochemical cycles and to suggest some priorities for research. Important financial support for the meeting and this publication was provided by the David and Lucille Packard Foundation. The World Wildlife Fund with its important conservation mission cannot be a major funder of biogeochemical research. But by means of this Workshop it is our hope that we will have underscored the need and highlighted some of the important questions in this critical field.

The Editors

Acknowledgement

Acknowledgement is made to the International Atomic Energy Agency and especially Peter B. Vose who worked hard to make the Workshop a reality, as an activity preliminary to the current IAEA/Government of Brazil Project BRA/0/010 in Amazon Baseline Ecology.

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EFFECTS OF DEFORESTATION ON SOURCES AND SINKS OF ATMOSPHERIC CARBON DIOXIDE, NITROUS OXIDE, AND METHANE FROM CENTRAL AMAZONIAN SOILS AND BIOTA DURING THE DRY SEASON: A PRELIMINARY STUDY.

GOREAU, T.J.[1], MELLO, W.Z.[2]

SUMMARY

Over 200 simultaneous sets of CO_2, N_2O, and CH_4 flux determinations to the atmosphere from virgin tropical rain forest, pasture, agricultural and secondary forest soils were made during mid 1984 in central Amazonia. They suggest that undisturbed rain forest soils are globally significant sources of atmospheric CO_2 and N_2O.

Large reductions in CO_2 releases to the atmosphere in the month after clearcutting, and measurements in bare soil suggest that about three fourths of soil CO_2 loss came from root respiration and the metabolism of fungi, insects, and bacteria dependent on living roots. CO_2 releases from young grassland and pasture soils were similar to those of virgin forest soils, but N_2O production was greatly reduced and soil was converted from consuming to producing atmospheric CH_4. CO_2 production from most secondary forest and agricultural sites was about half those of primary forest. A general decline in CO_2 recycling rate between atmosphere and biosphere via the soil increases residence time of atmospheric CO_2, lenghthening and heightening the effects of fossil fuel combustion and biomass destruction. Conservation of tropical productivity and recycling rates must play a major role if any efforts are made to manage the greenhouse effect.

Submerged forests and termites were major sources of CH_4, and are expected to increase in impact following deforestation. Seasonally flooded soils are large sources of N_2O when exposed, but submerged soils consumed it from the atmosphere. Within-site variability, lack of measurements in severely degraded secondary habitats, and sampling only during the dry season, make our results preliminary and unlikely to be representative of annual averages. Strongly seasonal rainfall and litter decomposition rates in central Amazonia indicate that year round sampling is required to quantify the differences between habitats and land usage practices as sources and sinks of atmospheric gases. Fuller understanding of the magnitude and mechanisms of carbon and nitrogen transfer from biosphere to atmosphere await long term measurements in conjunction with studies on productivity, biomass, litter fall, decomposition, and carbon and nitrogen inputs and outputs now planned by Brazilian researchers.

ALGUNS EFEITOS DO DESMATAMENTO SOBRE ALGUMAS FONTES E DEPÓSITOS DE DIÓXIDO DE CARBONO ATMOSFÉRICO, ÓXIDO NITROSO, E METANO DE ALGUNS SOLOS DA AMAZÔNIA CENTRAL E BIOTA POR UM PERÍODO DA ESTAÇÃO DAS SECAS: ESTUDO PRELIMINAR

RESUMO

Em meados de 1984 foram feitas na Amazônia Central acima de 200 determinações simultâneas de fluxos de CO_2, N_2O e CH_4 de solos de floresta tropical virgem, pastagens, áreas agrícolas e de floresta secundária, para a atmosfêra. Os resultados sugerem que os solos não perturbados da floresta úmida são fontes globais significantes de CO_2 e N_2O.

Grandes reduções na liberação de CO_2 para a atmosfêra no mês subsequente ao desmatamento, e medidas de solos nús, sugerem que três quartos do CO_2 do solo se perdem devido à respiração das raízes, e o metabolismo de fungos, insetos e bactérias que dependem de raízes vivas. A liberação de CO_2 de solos de gramados novos e pastagens foi semelhante à dos solos de florestas virgens, porém a produção de N_2O foi grandemente reduzida e o solo convertido de consumidor a produtor de CH_4 atmosférico. A produção de CO_2 da maioria das florestas secundárias e plantações agrícolas foi cerca de metade da observada na floresta primária. Um declínio geral no grau de reciclagem do CO_2 entre a atmosfera e a biosfera via solo

[1] Department of Geological Sciences, University of Miami, Coral Gables, Florida, USA.

[2] Division of Marine and Atmospheric Chemistry, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Florida, USA.

biomassa. A conservação da produtividade tropical e grau de reciclagem desempenha um papel de maior importância se se pretende controlar o "efeito estufa".

Florestas submersas e cupins são as maiores fontes de CH_4, e espera-se que aumentem com o impacto subsequente ao desmatamento. Solos alagados conforme a estação, são grandes fontes de N_2O quando expostos, porém solos submersos consomem N_2O da atmosfera. A variabilidade local, falta de medidas em habitats secundários severamente degradados, e amostragens somente no período da seca, formam nossos resultados preliminares e pouco prováveis de serem representativos de médias anuais. Chuvas pesadas na estação e os graus de decomposição da liteira na Amazonia Central indicam que é necessário fazer-se amostragens durante todo o ano, a fim de quantificar as diferenças entre habitats e práticas no uso da terra como fontes e armazenagem de gases atmosféricos. Uma compreensão total da magnitude e mecânismos de transferência de carbono e nitrogênio da biosfera para a atmosfera deve aguardar medidas a longo prazo em conjunto com estudos de produtividade, biomassa, queda e decomposição da liteira e "inputs" e "outputs" de carbono e nitrogênio, que estão sendo agora planejados por pesquisadores brasileiros.

Introduction

Numerous concerns have been raised about possible effects of tropical rainforest clearance and conversion to pasture or agricultural fields on soil fertility [1-14] and on atmospheric composition [15-19].

The potential effects of the current increase in atmospheric CO_2 (0.3% yr^{-1}) on global surface temperatures, rainfall, and sea level are well known. CO_2 emission to the atmosphere from biomass burning has been estimated from 2-5 x 10^9 tons-C per year[16-18], less than the amount now released annually from fossil fuel, 5.2 x 10^9 tons-C per year[21], and much smaller than the amount of CO_2 cycled to the atmosphere from the biosphere via soil, estimated at 5.3 x 10^{10} tons-C year[21].

Atmospheric N_2O is currently increasing around 0.2% yr^{-1} [22,23]. Increasing N_2O could lead to climatic warming and stratospheric ozone depletion over decades to centuries, causing increased ultraviolet radiation at earth's surface, increased genetic mutations, human skin cancer[24], eye cancer in livestock[25], and chlorophyll degradation[26]. These effects may be partially counteracted by increased "smog" ozone produced in the lower atmosphere (where roughly 10% of the ozone now lies) caused by increased releases of CO, NO and hydrocarbons from combustion and biomass decomposition [17,27-30].

At present, atmospheric CH_4 is rising 1-2% yr^{-1} [31,32]. Polar ice core measurements indicate that it has doubled over the past 150 to 300 years, with half the increase since 1950[33]. A greenhouse gas, CH_4 also interacts

These three gases are major regulators of global surface temperatures and of atmospheric ozone concentrations[34,35]. Relatively modest changes in natural biological sources and sinks of these gases could make large contributions to changing atmospheric composition, especially in environments in which carbon and nitrogen biogeochemical cycles reach their highest terrestrial production rates, such as tropical rainforests[35]. In this paper we report measurements of fluxes of CO_2, N_2O, and CH_4 between atmosphere and Amazonian rainforest, pasture, and agricultural soils during the dry season.

Sites

Climate: The Manaus area lies in the center of the world's largest remaining tropical rain forest and has an equatorial climate: mean annual temperature is about 26.5°C, seasonal variation of daily mean temperature is about 1°C, and diurnal variations are up to 10°C. Mean annual rainfall, about 2100 mm , is markedly seasonal and has strong temporo-spatial variability (W. FRANKEN, pers. comm.). The period of measurements reported here spans the height of the dry season[36].

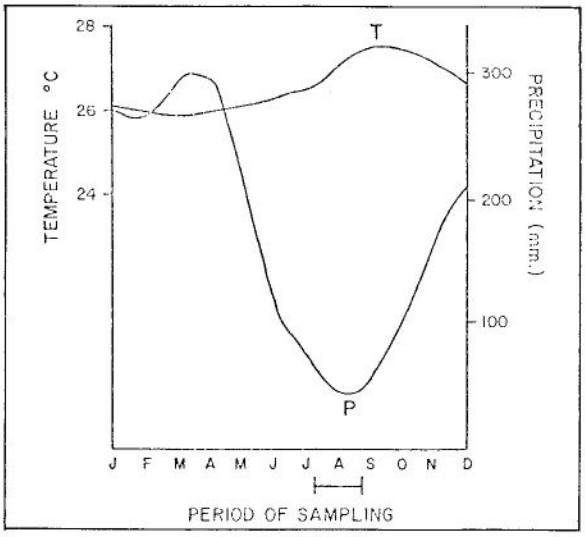

FIGURE 1 - The 6 week sampling period of this study (July-August 1984) occupies the historic dry season rainfall minimum in the area (after Nortcliff & Thornes, 1981)

Descriptions: (1) Porto Alegre and Esteio Ranches 60 km north of Manaus along the Boa Vista highway (BR-174) and road ZF-3. Porto Alegre and Esteio are adjoining cattle ranch - forest mosaics under current expansion, and sites of experimental forest reserves in the Biological Dynamics of Forest Fragments Project[37,38] of the World Wildlife Fund (WWF) and Instituto Nacional de Pesquisa da Amazonia (INPA). Long term ecological studies of floristics, biomass, production, and litter decomposition are underway at this site by INPA and WWF researchers (T. LOVEJOY,

P. FEARNSIDE, J. RANKIN, H. SCHUBART, & R. BIERREGAARD, pers. comm.).

At Porto Alegre gas fluxes were measured from soil sites in:

(a) undisturbed Terra Firme forest (on soils high enough to escape seasonal flooding) in the WWF-INPA 100 hectare Forest Reserve. A thin (0.5 to 1 cm thick) litter layer overlay yellow clay without a transition zone. Surface root mats were poorly developed. This forest type is the most abundant in Amazonia.

(b) recently clear-cut 1 x 0.3 km area. Underbrush had been cleared by machete two weeks, and trees felled by chain saw one week prior to the start of sampling. The forest floor beneath the tangle of recently felled vegetation was similar to that at site a. Most leaves of the felled vegetation dried attached to stems by the end of measurements one month later and there was only modest leaf addition to soil litter.

(c) one year old secondary growth (capoeira). This site had been cleared from primary forest but could not be burned due to wet conditions during the late 1983 dry season. One year later it had turned to an irregular 1-2 meter high tangle of felled trunks and young secondary vegetation. Few stumps had shoots, and vegetation was dominated by several species of rapidly growing "embauba" (Cecropia) trees and Passiflora vines. The original surface leaf litter layer had vanished, but twigs, branches, and boles lay on the greyish, bleached-looking soil surface. Actively growing secondary vegetation had supplied little fresh litter.

(d) grass (Brachiaria decumbens) field. Primary forest was clearcut and burned two years before, seeded, and allowed to grow without any grazing by cattle. A 0.5 to 1 cm thick black charcoal horizon overlay yellow clay, no surface litter was present, and unburned or scorched tree boles and branches were abundant. Chambers were placed in bare spots between 1 to 1.5 m grass clumps.

A 24 hour set of flux measurements were made from undisturbed tropical rain forest and from secondary growth about 100 metres away, at sites a and c above.

At Esteio gas fluxes were measured from the WWF-INPA 1 hectare forest reserve and from pasture which had been grazed by cattle for two years. Brachiaria decumbens was the predominant grass on slopes, but on heavily grazed areas atop flat interfluves it was subordinate to Brachiaria humidicola, said by ranchhands (pers. comm.) to tolerate poorer soils. Measurements were made on bare areas between grass clumps on flat high areas, slopes, bottom land, and on fresh and aged cattle manure.

Yellow Latosols (Brazilian classification, equivalent to ultisols) found at the sites above are the predominant soil type in Central Amazonia[39,40]. They are very acidic (pH about 4), have low cation exchange capacity (CEC)[41,42], and consist largely of kaolinite, quartz, and goethite [43] derived from weathering of the Tertiary Barreiras Formation. These sediments were eroded from the Precambrian Guyana and Brazilian Shields, deposited in the lake formed when the westward-flowing proto-Amazon was dammed by Andean uplift, and reexposed after development of the modern eastward flowing river system[44,46].

(2) "Reserva Biologica da Campina" (km 45 on highway BR-174). This INPA forest reserve has white-sand soil and a distinctive flora with pronounced sclerophylly, low diversity, and high endemism[47]. White quartz sand soils (Entisols) comprise less than one percent of the Brazilian Amazon[47]. They are often reworked river channel deposits formed during Pleistocene "glacial" periods, when the Amazon area was semi-arid with less forest cover and more erosion than today[48,51]. They are extremely nutrient poor and overlain by a thick intermingled root mat-litter layer[41,47,51,52].

Fluxes were also measured from sites which had been cleared and burned from campina forest 6 years and 11 years previously and used for experimental silviculture. At the first site, a mixed species plantation, trees were 8 to 10 m tall, charcoal was present on the surface, there was little or no surface litter, and ground cover by bracken and non-palmate lycopods was sparse. At the second site, adjacent, magnificent "Marupa" trees (Simaruba amara, a source of pharmaceutical compounds and termite resistant wood[54]) were 20 m tall. Palmate lycopods and grasses grew in several centimeters of leaf litter. The root mat was 15 cm or thicker at all virgin forest campina sites, but at silviculture sites the degraded organic mat was mixed with sand and from zero to 5 cm thick. Gas release from termite mounds of Nasutitermes and Heterotermes were measured in virgin and secondary campina forests using a large plastic bag.

Fluxes of gases across the air-water interface were monitored using a floating chamber in a lake caused by blockage of a stream (igarape) by the Manaus - Boa Vista Highway, permanently flooding the campina root mat and killing the trees. Measurements were taken in water about half a meter deep. To avoid disturbance the site was reached from above by climbing dead tree trunks.

(3) "Reserva Florestal Ducke" (Km 26 on the Manaus - Itacoatiara road). "Reserva Ducke" is a 10,000 hectare INPA forest reserve. Measurements were made in virgin forests along an elevation gradient:

(a) yellow clay soils found on higher sites. The litter layer was thin (0.5 cm or less), and palms were predominant in the undergrowth.

(b) yellow-brown sand-clay soils covered with a dense root mat (greater than 15 cm) found on lower slopes. Extensive measurements of soil and vegetation nutrient levels were made at this and the subsequent location by Stark[41].

(c) marshy soils above the bank of a stream. This site is flooded in the rainy season, but was 2-3 metres above stream level at time of sampling. Seepage (Figure 2) caused ponding of water in the lowest tenth of the surface of the soggy, brown, organic-rich soil. Moss-covered, buttressed tree trunks, palms, and a rich aroid and fern herbal stratum characterized this site.

of the Amazon Basin, but vary considerably in their characteristics[55].

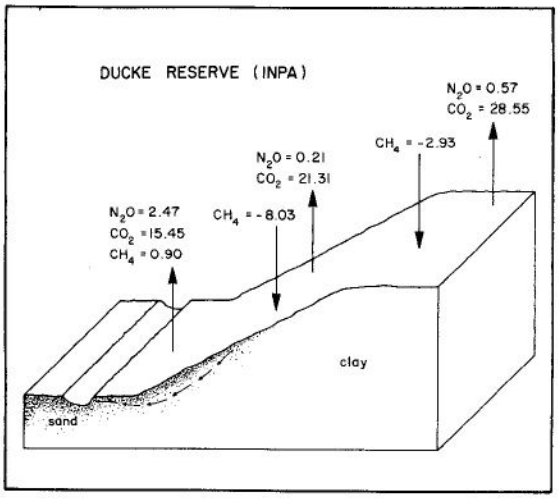

FIGURE 2 - Typical examples of chamber gas concentrations during the course of a fifteen minute flux measurement conducted simultaneously at four sites within 10 metres of each other. Fluxes (in molecules/cm^2/sec) shown were determined as the slope of the hand fitted curve at t=0.

(4) Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) Amazon Agricultural Experiment Station located at Km 30 on the Manaus - Itacoatiara road. Measurements were made in experimental fields which had been cleared and burned from primary terra firme forest three years before, ploughed and fertilized, and cropped to upland rice, soybeans, soybeans, cowpeas, corn, and cowpeas (T.J. SMYTH, pers. comm.). At the time of this study cowpeas had been cultivated for 2 months. Gas flux measurements were made in plots:

(i) cowpeas (Vigna ungiculata) with no fertilizer added since initial planting and fertilization two years before. It had very poor growth compared to fertilized plots.

(ii) cowpeas with additional fertilizers (P, K, N, Ca, Cu, Mo) added as required for good growth based on foliar analysis.

(iii) Cowpeas fertilized with P and with the organic residue from the previous cowpea crop ploughed underneath the heavy clay soil.

(iv) Bare soil ploughed and fertilized with P, K, N, Ca, Mo, and Cu after clearance (from secondary forest) one year before, and kept clear by thorough weeding.

(5) The Instituto Nacional de Pesquisas da Amazonia - INPA. Fluxes were measured in an old disturbed secondary forest site on INPA grounds which had been selectively thinned for charcoal kilns until 30 years ago (Dr. H. O. [illegible] canopy was more open, and termite nests and tracks were more common than at any other site examined. Soil conditions were markedly drier at this site, located within an expanding deforestation urban area, than at undisturbed forest sites. Gas release was also measured from hemispherical nests of termites of the genera Nasutitermes and Heterotermes using a large plastic bag, and fluxes were measured using a chamber from the major nest entry of the fungus-farming, leaf-gathering havester ant, Sauva (Atta sp.) after blocking visible side entries with dirt.

Methods

Gas fluxes between soil and atmosphere were measured using a quick, simple, and accurate chamber technique[55]. Low, thin, cylindrical metal chambers (diameter = 27.5 cm , height = 10 cm , thickness = .05 cm.) were inserted firmly but gently 1 cm into the soil surface. Sites were chosen by walking into visually undisturbed areas distant from paths, clearings, or forest edges, and choosing representative sites of forest floor. Domes were deployed four at a time, in pairs about 1 to 2 meters apart, separated by 5 to 10 meters. Soil temperature was measured by mercury thermometer at 2 cm depth at a number of sites nearby. Sampling followed a fixed order during late morning to early afternoon except for the diurnal experiment. Chambers, painted white, did not measurably change the soil surface temperature while emplaced. Surface litter was undisturbed except for a circular razorblade-like edge transecting individua leaves, a "footprint" which allowed repeated measurements of identical sites. When twigs, stems, or roots prevented emplacement the chamber was redeployed nearby. Tough near surface grass root networks caused two flux measurements in pasture to be rejected because improper chamber sealing was indicated by non-smooth gas evolution curves.

20 cc gas samples were collected from the chamber headspace via stopcock into doubly-ground glass syringes immediately after emplacement and at 5, 10, and 15 minutes. During sampling, chamber pressure was kept constant by admitting an equal volume of ambient air via another stopcock. Stopcocks were removed to prevent pressure gradients during dome emplacement. Field tests repeatedly using chambers between half hour rest intervals did not perturb the measured flux[55]. Almost all data points lay within one analytical standard deviation of a smooth temporal evolution curve (eg. Figure 3), and were always adequate for accurate determination of initial fluxes. Downward curvature induced by back diffusion was noted at sites producing large amounts of CO_2 and upward curvature at sites of high CH_4 consumption. N_2O production in the same samples were close to linear in all but sites with highest fluxes, which showed downward curvature (Figure 2).

All samples used in this study were stored in dry syringes in a cooler at ambient temperature and analyzed immediately on

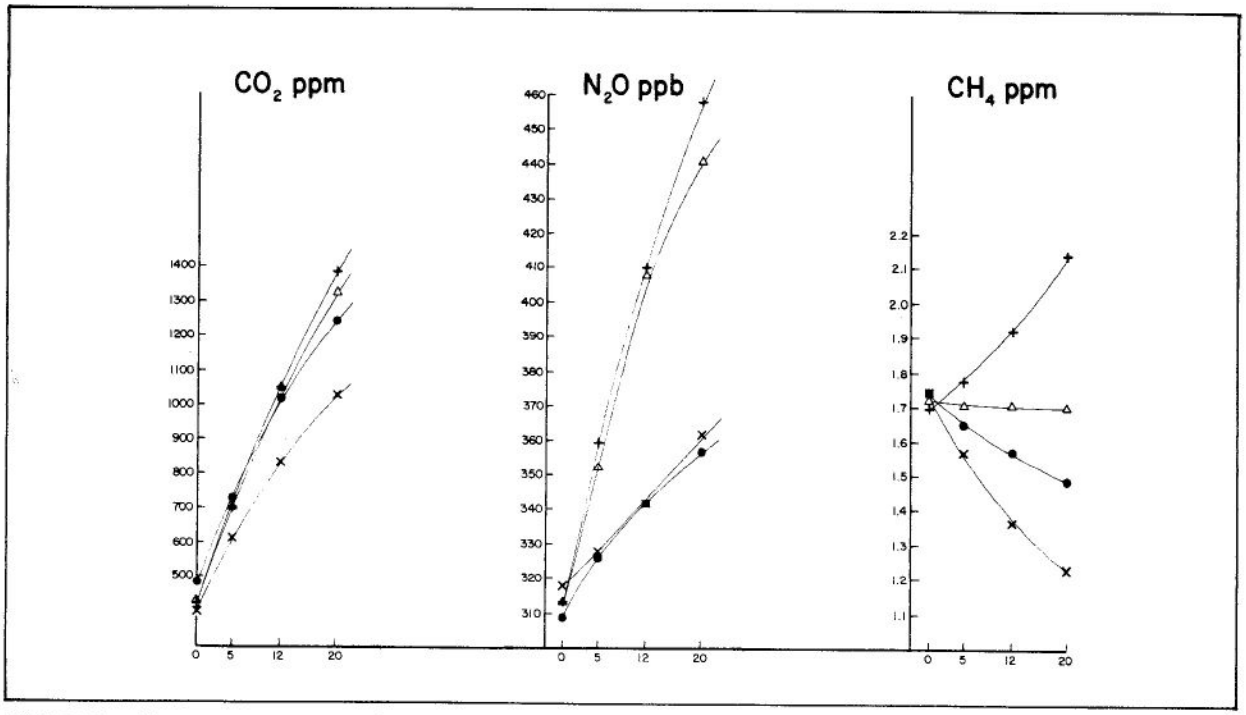

FIGURE 3 - Time series of gas fluxes from four sites in secondary forest within 10 m of each other. The site that produce CH_4 was located 0.5 m from a recently abandoned termite mound.

return to the laboratory. All samples were analyzed within 24 hours of sampling. Storage tests revealed that air samples stored dry in syringe in a room containing high levels of CO_2 changed by around 3% after a day. Air stored in outside air in plastic bags in the same room did not change after 2 days, indicating diffusion along the syringe barrel, not formation in the syringe, was responsible. Gas samples stored in syringe with a distilled water seal between barrel and plunger in an attempt to slow molecular diffusion had large and variable concentrations of all three gases, presumably from growth of bacteria in the air sample on wet glass surfaces. Those syringes continued to give anomalously high values and were rejected.

A Shimadzu gas chromatograph equipped with thermal conductivity, flame ionization, and electron capture detectors was set up in the Wood Entomology Laboratory at INPA. Samples were injected from the sampling syringe via a luer-fitted stopcock through a trap containing dry ice (- 70°C) to remove water vapor, into serial injection loops (2 ml, 1 ml, and 1 ml for N_2O, CO_2, and CH_4 respectively). The three parallel separation columns were filled with Porapak Q. Oven temperature was 23°C. The temperature of the ECD and TCD were respectively 350°C and 150°C. Analytical precision was around 1% for the 3 gases at atmospheric concentrations, based on replicate standard and air analyses. Minimum detectable emissions were about 6×10^8, 6×10^{11}, and 4×10^8 molecules cm^{-2} sec^{-1} for N_2O, CO_2, and CH_4, respectively.

Results

Mean gas fluxes from each habitat, their standard deviations, and the number of replicates are listed in Table 1. Variance is several orders of magnitude greater than the analytical precision. Variance results from a) real within-site variability in each habitat indicated by consistent differences between systematically reoccupied sites and b) general temporal trend over the six week sampling period (Figure 4). Every habitat with large within-habitat variability (Table 1), contained subpopulations of sites with much smaller variance: a) some sites in undisturbed rainforest and in old secondary forest were systematically higher or lower N_2O or CH_4 consumers or producers (Figure 3), b) exposed, seasonally flooded river-bank forest included sites which produced large amounts of N_2O or which were modest producers, and c) sites in those cowpea fields which had had the previous crop ploughed under had equal numbers of sites with high release of N_2O and CH_4 and those which were similar to cowpea fields which had not been green-manured. Heterogeneous distribution of litter abundance and quality, roots, nutrients, soil, fauna, fungi, mycorhizae, bacteria, and moisture may explain much of the variance observed. We were not able to quantify those parameters in this study.

Carbon Dioxide: Table I indicates that:

(1) Virgin forest soils released the largest mean amount of CO_2, 25.75×10^{13} molecules/cm^2/second (n=69).

(2) Waterlogged and inundated forest soils released less CO_2 than upland forests.

(3) Secondary forest soils gave off less CO_2 than primary forest, generally about half. Only the oldest silviculture site was similar to virgin forest.

(5) Agricultural sites released CO_2 at rates similar to those of secondary forest.

(6) The lowest values were found from soil which had been kept bare of vegetation for one year since clearance and from flooded soils.

TABLE 1
GAS FLUXES FROM CENTRAL AMAZON SOILS

	GAS FLUXES IN MOLECULES/CM^2/SECOND CO_2 x 10^{13}	N_2O x10^{10}	CH_4 x10^{10}
1) VIRGIN FORESTS			
A) Clay soils			
i) Porto Alegre (n=20)	27.27 ± 12.86	1.49 ± 1.43	-1.58 ± 4.86
ii) Esteio (n=4)	20.51 ± 11.00	.97 ± .58	-5.75 ± 2.00
iii) Ducke (n=12)	28.55 ± 12.63	.57 ± .30	-2.93 ± 1.49
B) Sandy soils			
i) Ducke (n=12)	21.31 ± 6.58	.21 ± .14	-8.03 ± 3.39
ii) Campina (n=11)	36.07 ± 12.84	.38 ± .56	-6.82 ± 4.20
C) Seasonally Flooded Forest soils			
i) Ducke (n=10) (dry)	15.45 ± 7.48	2.47 ± 3.65	.90 ± 1.46
ii) Campina (n=9) (wet)	3.88 ± 2.36	-.25 ± .25	2,360 (*)
2) SECONDARY VEGETATION			
A) Clay soils			
i) Clearcut (n=30)	15.45 ± 7.10	.58 ± .56	-5.02 ± 2.92
ii) Capoeira (n=20)	15.20 ± 3.53	.81 ± .37	-3.23 ± 2.24
iii) Forest (n=36)	15.38 ± 2.96	1.45 ± 1.05	-2.67 ± 8.49
B) Sandy soils			
i) 7 yr forest (n=4)	12.57 ± 4.40	.235 ± .307	-5.88 ± 1.35
ii) 11 yr forest (n=3)	29.07 ± 4.99	.36 ± .01	-6.54 ± .44
3) PASTURE			
i) Ungrazed (n=14)	24.32 ± 7.10	.11 ± .18	-.22 ± 2.33
ii) Grazed (n=9)	20.82 ± 3.04	.19 ± .41	1.13 ± 2.02
4) AGRICULTURE			
i) (n=4)	15.77 ± 3.91	.85 ± .37	-2.30 ± 1.09
ii) (n=4)	16.57 ± 1.62	.14 ± .11	-1.61 ± .79
iii) (n=4)	18.41 ± 5.74	2.14 ± 2.86	8.06 ± 14.69
iv) (n=4)	6.21 ± .99	.72 ± .33	-1.92 ± .50

Key:
i) No fertilizer ii) Complete fertilizer: P, K, Mo, N, Ca, Cu
iii) P, green manure iv) Bare soil, complete fertilizer

Nitrous Oxide: Table I suggests that:

(1) N_2O fluxes were highest from exposed marshy river bank virgin forest ("igapo") soils and from agricultural plots in which nitrogen rich cowpea crop residues and phosphate fertilizer had been ploughed into the heavy clay.

(2) Comparable mean values of N_2O release were observed from primary forests, secondary forests, and from agricultural sites on clay soils.

(3) Much lower releases occurred from both primary and secondary forests on sandy soils than those on clay soil.

(4) Very low fluxes were found from grassland and pasture.

(5) Minor N_2O consumption was found by waters overlying submerged campina forest.

(6) N_2O fluxes showed greater within-habitat variability than CO_2 fluxes. This was largely caused by lumping together of soil subpopulations with different N_2O emission characteristics.

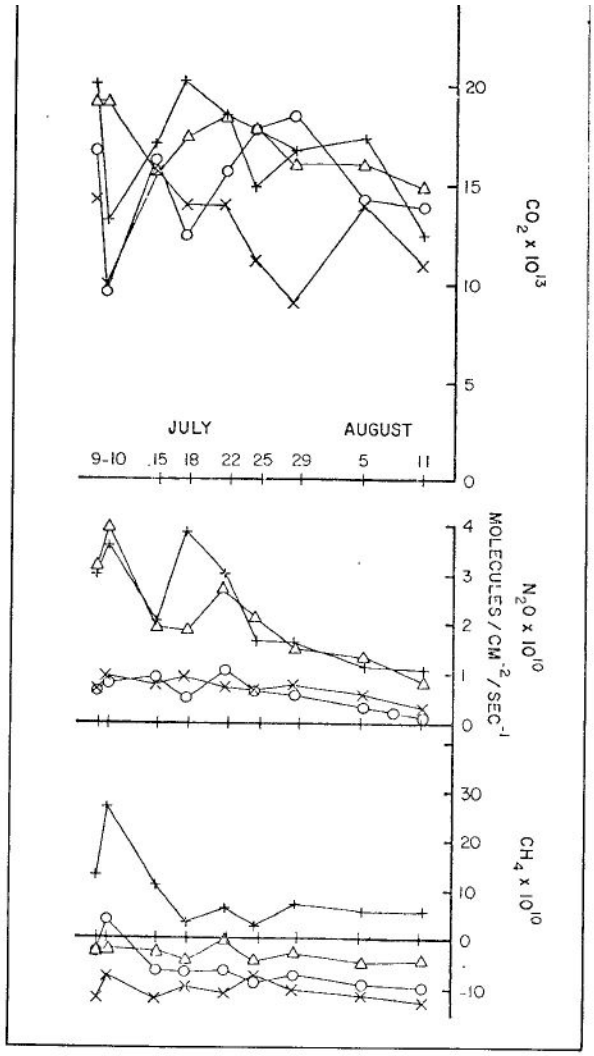

FIGURE 4 - Diagram of soil types and inferred path of water flow through sandy soils to seeps near the igarape (creek) at Reserva Ducke. Mean gas fluxes are indicated in units of 10^{10} molecules/cm^2/sec for CH_4 and N_2O and in 10^{13} molecules/cm^2/sec for CO_2.

Methane: Table I indicates:

(1) CH_4 was consumed from the atmosphere at comparable rates by virgin forest soils, except for waterlogged river bank soils, which were a small source of the gas (Figure 2).

(2) Modest CH_4 release was observed from cow manure with a roughly millimeter thick dry crust and moist interior, but it was consumed at sites with fragments of decomposed manure.

(3) CH_4 was released from half of the agricultural sites where cowpea crop residues had been ploughed into the soil, the others consuming it.

(4) Extremely high release of CH_4 was found from water surfaces overlying flooded

campina, similar to that of CO_2. CO_2 and N_2O changed smoothly in floating chambers, but CH_4 concentrations were subject to sudden jumps, indicating major transport via bubbles rather than diffusion. Consequently, 9 separate flux determinations were made for CO_2 and N_2O in this habitat, but all 36 measured CH_4 concentrations were pooled to compute a single mean CH_4 flux.

Changes in a Clearcut Forest Site: One month after clearance mean CO_2 fluxes decreased sharply by two thirds (Figure 5). Initial average N_2O fluxes were initially less than values in undisturbed forest, but roughly doubled over the month after cutting. CH_4 consumption showed no marked change. This sampling period covered about half the normal interval before burning.

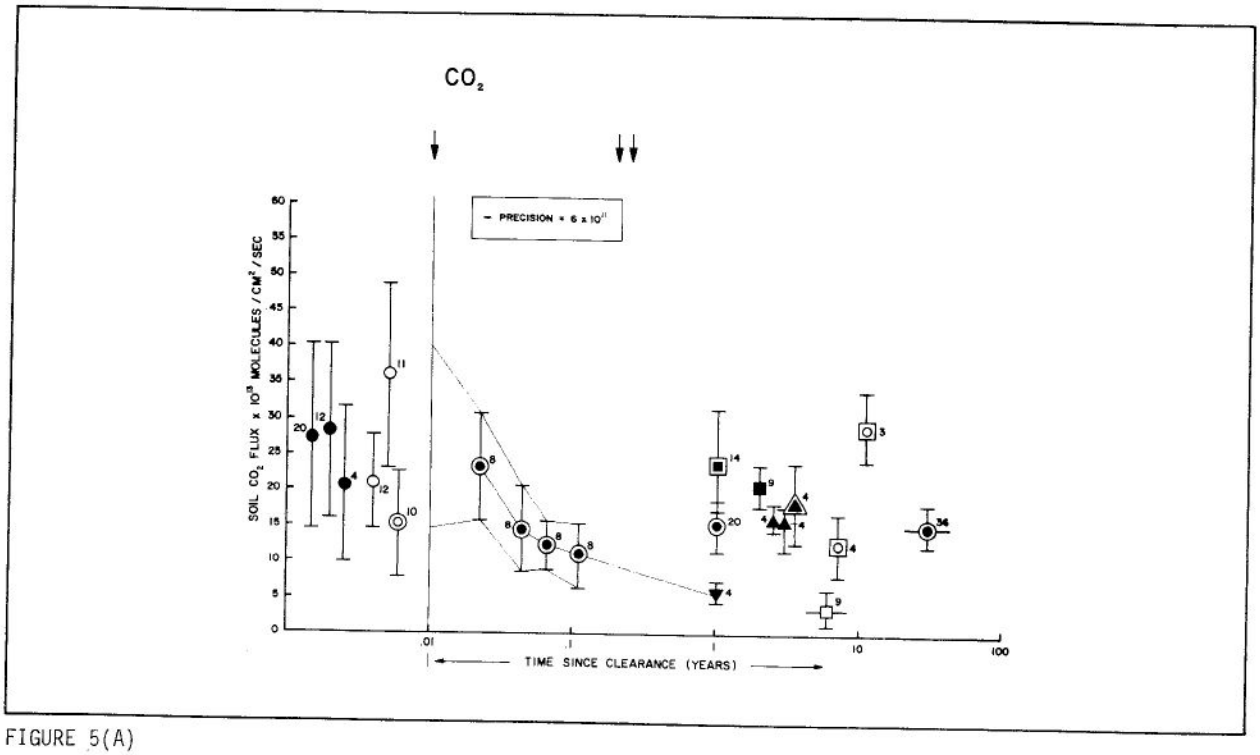

FIGURE 5(A)

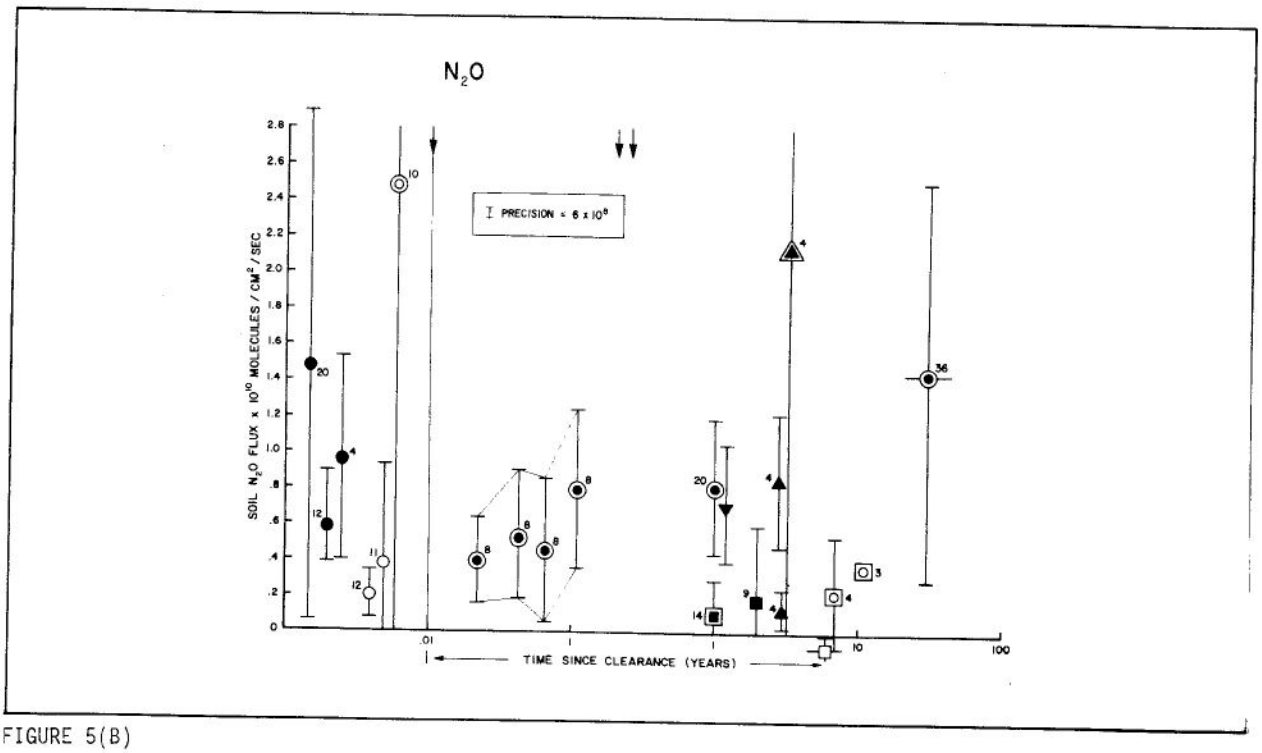

FIGURE 5(B)

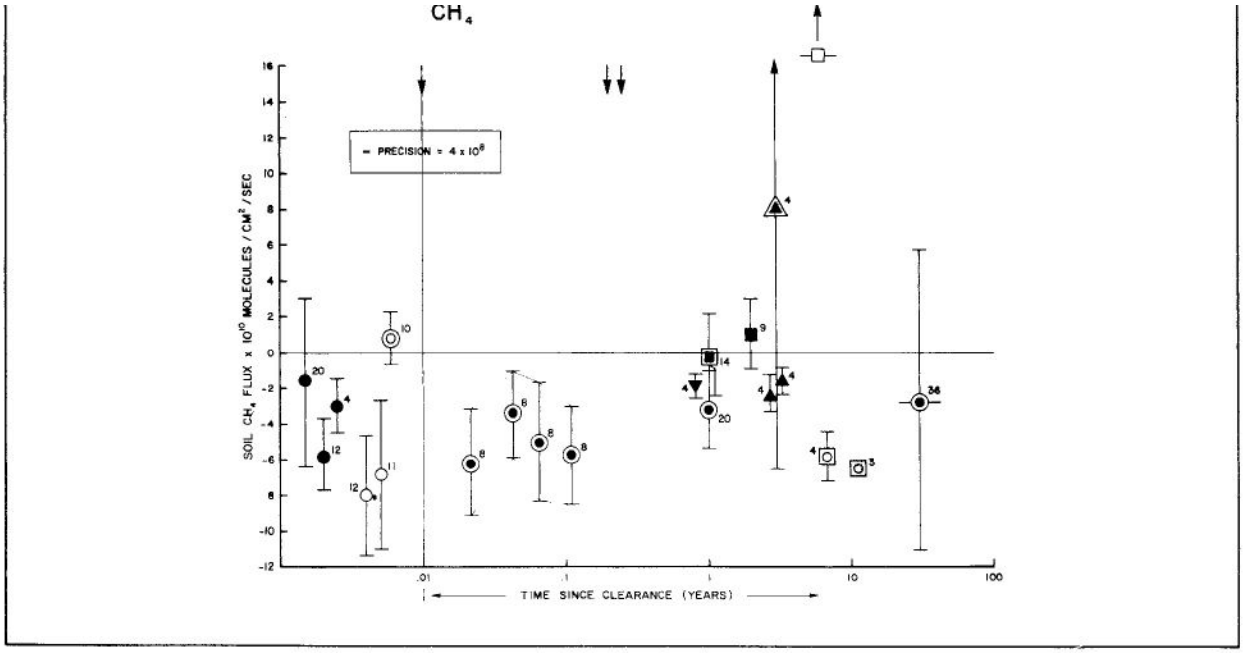

FIGURE 5(C)

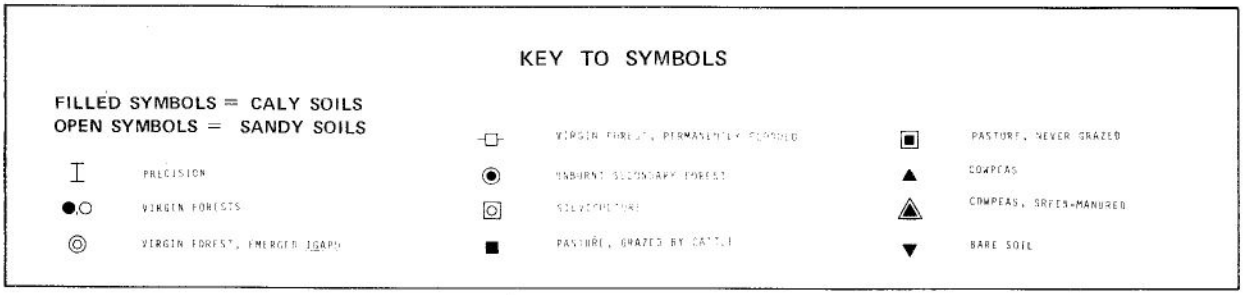

FIGURE 5(D)

FIGURE 5 (A, B, C, D) - Data of Table 1 plotted to show fluxes of gases from soils in virgin forests at left, and secondary habitats plotted against the log of the time in years since disturbance. The numbers by each symbol indicate the number of flux determinations. Symbols indicate land usage and soil type. Sampling did not cover the important interval from 2 months to 11 months after clearance, when large transient sources of all three gases are expected. The error bars indicate the sensitivity of individual flux measurements as ± the minimum detectable flux. The left hand arrow at top indicates time of forest clearance, the central arrow time of burning, and the right arrow indicates the start of the rainy season and rapid decomposition of uncombusted litter.

Diurnal Variation: A simultaneous diurnal comparison was made between a virgin forest site and one nearby which had been clearcut one year before and abandoned to regrowth without burning. Air and soil temperatures, and their variations, were higher in secondary capoeira forest than in undisturbed forest (Figure 6a), as secondary growth was much less effective in shading the ground from solar radiation. A clear, sunny day was terminated by a sudden downpour at 13 hours which dropped 16 mm of rain in 15 minutes, dramatically cooling soil and air, and ending a dry spell (only 3 mm of rainfall accumulated in a raingauge located between the two sites during the entire proceeding week). Diurnal variation of N_2O and CO_2 emission and CH_4 consumption during August 3 to 4 are shown in Figures 6b, c, d. N_2O showed the largest flux variation in capoeira, and the smallest in virgin forest. Capoeira N_2O production rose sharply as soil warmed, and continued to rise further after soil was cooled and wetted at 13 hours, reaching rates in late afternoon approximately 14 times higher than early

morning. Rain forest N_2O production, in contrast, had only minor diurnal fluctuations. Daily variation of CO_2 emission and CH_4 consumption (Figure 6a) follow similar patterns in forest and capoeira, with no more than a threefold daily amplitude range. Minimum values were found during early morning and maximum during the afternoon, and both declined following the rainstorm. Average CO_2 emission rates from forest soil were about 50% larger than from secondary growth. Phosphorescent fungi dotted the forest floor, but were not noticeable in the Capoeira.

Insects: Termites were a significant source of CH_4 in Amazon habitats (Table 2). One soil site in disturbed secondary forest 0.5 m from a termite mound consistently released CH_4 (Figure 3). The mound itself, though fresh in appearance, did not release CH_4 and subsequent excavation showed it was abandoned. Similar results from branches formerly occupied by termites suggest that live termites, not fungi growing in their tunnels, were responsible. Live colonies of Nasutitermes sp. released about 1.5% as many CH_4 molecules as CO_2, while Heterotermes sp. colonies released about 0.25%. Both species are regarded as moist wood feeders[57]. Small amounts of N_2O were also released by all colonies except one, which consumed it. One flux measurement was made over the mouth of a large colony of the leaf cutting ant, Atta sp.. These ants carry freshly cut leaves for decomposition in their nests by obligately symbiotic fungi. No change in CH_4 concentration occurred at the nest entrance, N_2O flux was one-third less than nearby soil, and CO_2 release was about twice as large.

TABLE 2

GAS PRODUCTION BY INSECT COLONIES

INSECTS	LOCATION	DATE	CH4/CO2	N20/CO2
		TERMITES		
Heterotermes	INPA	July 9	3.3×10^{-3}	6.2×10^{-5}
Heterotermes	INPA	July 15	2.65×10^{-3}	1.6×10^{-5}
Heterotermes	Campina	July 16	1.44×10^{-3}	3.1×10^{-5}
Nasutitermes	INPA	July 22	9.2×10^{-3}	1.3×10^{-5}
Nasutitermes	Campina	July 23	22.3×10^{-3}	-2.82×10^{-5}
Abandoned mound of Heterotermes	INPA	July 15	0	-
		ANTS		
Atta sp., leaf-cutting "Sauva"	INPA	July 9	0	6.2×10^{-5}

MEAN GAS PRODUCTION RATES BY AMAZONIAN TERMITES

CH4/CO2	$7.78 \pm 7.74 \times 10^{-3}$	(n=5)
N2O/CO2	$1.14 \pm 2.08 \times 10^{-5}$	(n=5)

TABLE 3

COMPARISON OF GAS FLUXES FROM SELECTED HABITATS

(CO2= TC/ha/yr N2O= KgN/ha/yr CH4= KgC/ha/yr)

AUTHOR	LOCATION	FOREST TYPE	CO2	N2O	CH4	n
This study	Amazonia	primary forest	16.2	1.54	-2.19	69
Goreau 1982	Hubbard Brook	temperate	7	.2		120
Keller 1983	"	"			-1.1	108
"	Amazonia	tropical		3.81	-.9	13
Christensen	Denmark	pasture		1.8-5.1		72
This study	Amazonia	pasture		.3		9
"	"	grassland		.2		14
Medina	"	laterite	2.7			70
"	"	podzol	3.6			70
Schulze	Costa Rica	wet primary	37.8			4
"	"	secondary	61.0			4
Raich	"	primary	12.4			28
"	"	secondary	16.8			27
Wanner	Java	primary	8.1			24
"	Borneo	"	10.1			24
Anderson	Sarawak	"	5.8			150
Ogawa	Malaya	"	14.2			36

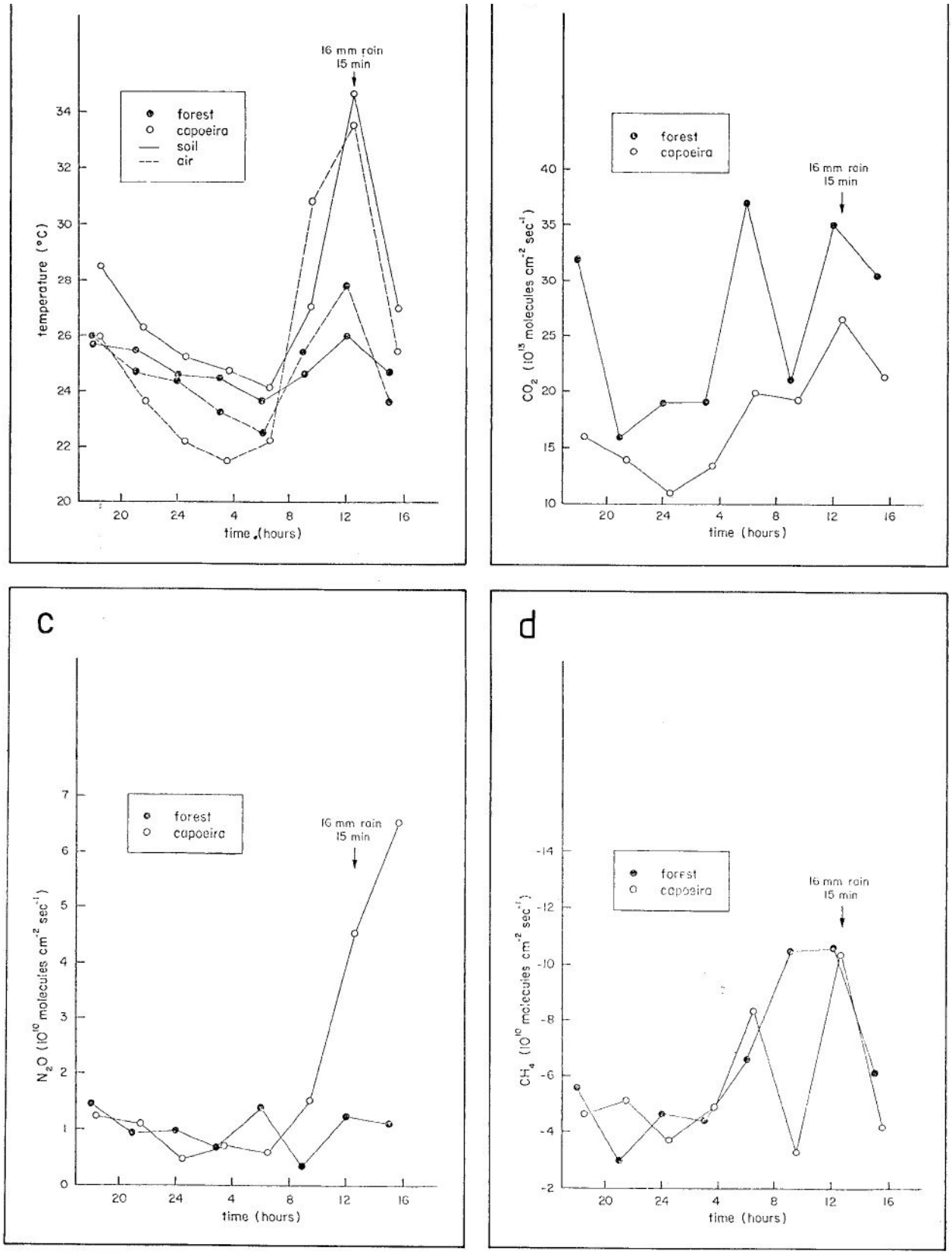

FIGURE 6 - (a) Diurnal soil and air temperature cycles, (b) CO_2 fluxes, (c) N_2O fluxes, and (d) CH_4 fluxes in the WWF/INPA 100 ha forest reserve and in one year old secondary forest (capoeira) at Fazenda Porto Alegre.

Discussion

Carbon Dioxide: Table 3 lists mean fluxes from Amazon environments in Tons or Kilograms of Carbon or Nitrogen emitted per Hectare per year, assuming that measurements are a first order estimate of year-round production or loss. Values reported from other similar environments are also listed. Different methods used make intercomparison problematic as most CO_2 fluxes are based on absorption of CO_2 from a chamber by a KOH trap during 8 to 24 hour emplacements. A correction factor is applied since about 1/4 of CO_2 is not absorbed by the base. Long incubation times used in absorption methods can alter soil to air concentration gradients and fluxes within 5 to 10 minutes (Figure 2).

CO_2 fluxes reported here are very similar to those reported from forests in South East Asia [58-60]. They were considerably higher than those reported from the Venezuelan Amazon[61] (located over Precambrian shield rocks and even more poor in nutrients than Central Amazonia), but considerably less than values reported from Costa Rica[62] (an area of nutrient rich soils). Our data indicating higher CO_2 release from primary forest than secondary vegetation is in disagreement with data from Costa Rica[63], and our data showing higher CO_2 production during the day than night is in disagreement with results from Venezuela[61].

The predominant source of CO_2 from Amazonian soils appears to be root respiration and root-dependent metabolism, rather than litter and soil organic matter decomposition. This is indicated by a) the two-thirds decline in CO_2 release immediately following deforestation, although the litter layer and roots were intact, and b) the low values (one-fourth that of forest) found from bare soil cleared from forest one year before. Our rough estimate that about two-thirds to three-fourths of CO_2 released is derived from root and root-dependent respiration for yellow latosol forest soils is very close to that of 67% to 82% from campina forests in Venezuela[61], based on measurements of CO_2 trapped before and after separation of superficial root mats from underlying sands. Like ours, those estimates combine root respiration and heterotrophic respiration dependent on metabolites derived from living roots such as vesicular-arbuscular mycorrhizal fungi, root-plane ectomycorrhizal fungi and bacteria, and root phloem or xylem feeders such as many larval and adult insects.

CO_2 release from grassland and pasture soils is similar to that of the undisturbed forests which they replaced, and higher than that of secondary forests or of agricultural sites. Grass and pasture sites have vastly reduced biomass and litter production compared to virgin jungle, making their similar soil CO_2 release surprising. Grassland apparently has much higher respiration per unit biomass than forest, possibly because of higher temperatures in cleared pasture, which were similar to those in capoeira. High respiration losses of carbon fixed in photosynthesis are unexpected since Brachiaria has a C-4 (PEP Carboxykinase) photosynthetic pathway[64], and should have low rates of photorespiration. Large grassland soil CO_2 losses could be an unsustainable short-term transient due to fertilization by nutrients in ashes and cow manure.

Overgrazed pastures and pastures abandoned to secondary forest were seen from the Manaus-Boa Vista highway. The former had markedly lower grass biomass and soil coverage than the vigorously growing and relatively recently burnt plots studied. Embauba (Cecropia sp.) trees, which accounted for most young secondary forest biomass, appeared to have smaller leaves, thinner stems, and more leaf insect damage in capoeira succeeding abandoned pasture than in the plot studied, which had not been burnt or used for pasture. Most roadside farms were clearly far less productive than the experimental agricultural sites studied, and the older pastures more degraded. Because we did not have the opportunity to sample representative areas of longer utilized secondary habitats, the CO_2 releases reported here from secondary habitats and agriculture are probably on the high side for their class.

A general decrease in CO_2 release from soil following deforestation is a reflection of decreased net primary production and declining soil fertility. A slowed carbon recycling rate between atmosphere and biosphere leads to an increased CO_2 atmospheric residence time. Rather than counterbalancing combustion CO_2 inputs, the net effect of this decrease could be to lengthen and heighten the climatic impact of fossil fuels. Land management practices which degrade productivity and reduce rapid carbon recycling should be avoided if any effort is to be made to manage the greenhouse effect.

Nitrous Oxide: Gaseous losses of nitrogen from soils can occur as N_2 (by denitrification), NH_3 (by volatilization and aerosols), and N_2O (by nitrification and/or denitrification). Volatilization is insignificant in Amazonian soils due to low pH (3.8-4.2)[12]. Denitrification cannot occur in aerated soil but is common when waterlogged conditions and high respiration promote anoxia. However, denitrification tends to act as a nitrous oxide sink because N_2O is the energetically favored terminal electron acceptor in the absence of oxygen. Nitrification requires molecular oxygen, but can proceed at low oxygen levels, which greatly favor N_2O production by nitrifying bacteria[65].

Undisturbed Amazon rainforests are currently a major global source of N_2O which sharply decrease following conversion to pasture. The decrease, like that of CO_2, will be balanced to some extent by short term release from a) combustion of biomass, and b) elevated decomposition and nitrification early in the rainy season while the ground is still bare after burning and before grass seedling roots are established. Unfortunately, the magnitude of these effects cannot be estimated from existent data. The matter deserves further attention because stratosphere ozone is primarily destroyed by NO derived from N_2O, but NO released directly from the soil surface increases photochemical smog ozone in the lower atmosphere[66-70]. Sources of NO, like N_2O, include nitrification, denitrification, and

Amazonia had lower N_2O production rates than temperate grasslands[72], where up to 50 mg N_2O emission m^{-2} day^{-1} came from grassland soil 5-10 days after application of cow manure, decreasing to that of untreated grass 4 weeks later. In contrast, there was little or no N_2O release from Amazonian manure. This could occur if the C/N ratio of Amazon cattle dung is sufficiently high to immobilize nitrogen rather than release it, that is, under conditions of nitrogen deficiency. The 5 to 10 fold lower N_2O releases observed from pastures than from forest soil may result from more rapid and efficient recycling of ammonium ions in grasslands than in forests. Nitrification is greatly inhibited in grassland soils[1] due to competition from dense subsurface grass roots and/or allelochemical effects[73]. N_2O release to the atmosphere should consequently decline after deforestation, remain low during pasture usage, and recover when secondary forest is reestablished.

The lower N_2O losses from campina forests with well developed root mats are in accord with the direct nutrient cycling hypothesis[74,53], which suggests that nitrogen and other nutrients are directly recycled to trees via root-associated fungi resulting in low soil nitrate concentrations and small soil nitrifying bacterial populations[75]. Roots and mycorrhizae were observed to cover and penetrate leaf litter and the cambial layers of fallen twigs and branches at our sites, especially in campina forest. Amazonian white sand forest tree roots are closely associated with ectomycorrhizal fungi, which are rare in clay soil forests[76]. Conversely, most clay soil forest trees are infected with vesicular-arbuscular ectomycorrhizal fungi, which are rare in sand forests[77]. Endomicorrhizae largely include Basidiomycete saprophytes, which have polyphenol oxidases and directly decompose litter, resulting in a closed nitrogen cycle, but endomycorrhizae are unable to break down litter directly and depend on nitrogen released by bacterial intermediaries[78]. Presumably a larger fraction of ammonium released by decomposition is then available in soil to nitrifying bacteria.

Comparable values (about 14 kg-N ha^{-1} yr^{-1}) have been reported[11,53,79] for nitrogen input by rainfall and the output by stream discharge in a forest at San Carlos de Rio Negro, Venezuela. A nitrogen balance in the Amazon basin has been proposed[80] consisting of: 6 kg-N ha^{-1} yr^{-1} input via precipitation, 20 kg-N ha^{-1} yr^{-1} input via biological nitrogen fixation, 6 Kg-N ha^{-1} yr^{-1} output via Amazon river, and by difference, 20 Kg-N ha^{-1} yr^{-1} of loss by "denitrification" and volatilization. Our results suggest nitrogen loss as N_2O is between 1.4 and 2.2 Kg-N ha^{-1} yr^{-1}. If gaseous nitrogen losses estimated by partial mass balance calculations are correct, N_2O can be only a small part of them. If nitrification is the major source of N_2O, an equivalent amount of NO and up to 300 times more nitrite and nitrate N should be produced depending on the oxygen concentration at nitrification losses. Nitrification rates are especially high in the tropics, and are often greatly elevated following forest clearance[1,81,82]. Unfortunately, little data is available on nitrification or on nitrate leaching from Amazonian soils.

Methane: Amazon terra firme forest soil CH_4 consumption rates are about three times those reported at temperate Hubbard Brook (0.29 mg-C m^{-2} day^{-1}) and Bacia Modelo, Amazon, (0.28 mg-C m^{-2} day^{-1})[83]. Extrapolating terra firme soil CH_4 consumption rates to 10^9 ha of rainforest would provide an atmospheric output of about 3×10^6 ton-C per year, a small fraction (§ 1%) of CH_4 removed annually in the troposphere by reaction with hydroxyl radicals.

Atmospheric CH_4 is produced at the earth's surface by anaerobic bacteria in anoxic organic-rich environments such as waterlogged soils, swamps, marshes, sediments, and in the intestines of ruminant herbivores. CH_4 oxidizing bacteria are aerobic, and similar in many biochemical, physiological, and ecologic regards to ammonium-oxidizing nitrifiers. Though termites have long been known to produce CH_4, CO, and H_2[84], there has been recent controversy over the importance of termites as CH_4 sources[85-87]. The mean CH_4/CO_2 production ratio of Amazonian termites studied suggests that only around 2-3 per cent of CO_2 release need take place via termites to balance local soil CH_4 consumption. While no estimates for termite carbon processing could be found for this area, studies in tropical forest and savannah environments in the Old World suggest that termites harvest from a few percent to as much as a third of litter and wood[88]. Thus termites could provide the source of much CH_4 consumed in Amazon soils. However, fluxes from the flooded forest soils were so high that only about 0.2 per cent of the area need be covered by this habitat to supply soil consumption.

Effects of deforestation include:

(1) increase in area of permanently flooded soils upstream of road culverts and reservoirs,

(2) increase in termite nest density due to increased availability of large dead trunks and branches,

(3) increase of cattle and their manure, and

(4) increased methane released from combustion of biomass, so the net effect of forest conversion should be to increase atmospheric CH_4 . Extensive permanent and seasonal flooding of forest soils is expected shortly at the Balbina Hydroelectric Project, located in the watershed to the north. The shallow reservoir that will result has numerous islands and inlets, and the extremely long residence time of water in the reservoir makes anoxic conditions likely (Dr. M. KRITZ, Laboratorio Nacional de Computação Científica, pers. comm.). The region would be expected to become a larger CH_4 atmospheric source in consequence.

Conclusions

Our data confirm that tropical biosphere alterations play a significant role in the present balance of atmospheric CO_2, N_2O, and CH_4, and show that qualitatively different patterns of gas evolution results from several of the major land usage patterns now practiced in Central Amazonia. We have avoided detailed statistical interhabitat or land management comparisons based on these data, as indicated in the word "preliminary" in the title, because:

(a) measurements were made only during mid dry season and are unlikely to equal mean annual values. Large seasonal differences in litter fall and decomposition rates occur in the area[89].

(b) measurements do not include CO_2 exchange between above ground vegetation and the atmosphere, releases of CO_2, CH_4, and N_2O from combustion of biomass, nor the pulse expected from accelerated decomposition of unburned biomass early in the rainy season. Before grass or crops are established, nitrifiers face little root competition for ammonium[33], and it is predicted that N_2O releases should be especially high at that time.

(c) a wider variety of representative habitats and land usage practices need to be examined.

Reliable quantitative forecasts of the net effects of deforestation on atmospheric composition require much more information on biosphere-atmosphere gas exchange than now available. When coupled to biomass, productivity, and nutrient balance studies such as those in progress or planned at INPA and other Brazilian and foreign institutions, gas flux measurements can provide insight into the rate of loss and the efficiency of cycling of carbon and nitrogen in these ecosystems and help provide guidelines on the long term environmental effects of their utilization and conservation[91].

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