Hydroelectric Dams in the Brazilian Amazon as Sources of 'Greenhouse' Gases

by

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INTRODUCTION

Hydroelectric dams are commonly believed to have no serious impact on the 'greenhouse effect', in contrast to fossil-fuel use. However, the principal reason for this frequent assumption is ignorance regarding the emissions of hydroelectric dams. Reservoirs in Brazilian Amazonia (Legal Amazon) contribute to 'greenhouse' gas emissions from the region, although contributions from currently existing reservoirs are small relative to other anthropogenic sources such as deforestation for cattle pasture. The four existing 'large' (> 10 megawatt [MW]) dams in the region are: Balbina in the State of Amazonas (filled in 1987), Curuá-Una in Pará (1977), Samuel in Rondônia (1988), and Tucuruí in Pará (1984) (Fig. 1). In addition, there are small reservoirs at Boa Esperança in Maranhão (filled prior to 1989), Jatapu in Roraima (1994), Paredão or Coarcy Nunes in Amapá (1975), and Pitinga in Amazonas (1982).

The scale of hydroelectric development contemplated for Amazonia makes this a potentially significant source of emissions of 'greenhouse' gases in the future. Existing and planned dams are shown in Fig. 2 and listed in Table I. Brazil's financial difficulties have repeatedly forced the national power authority (ELETROBRÁS), and the power monopoly in northern Brazil (ELETRONORTE), to postpone dam-building plans. However, the overall scale of the plans, as distinguished from the expected date of completion of each dam, remains unchanged and consequently an important consideration for the future.

Little basis exists for calculating emissions from reservoirs. However, existing information can be organized in such a way as to draw the best possible conclusions given the limitations of our knowledge. The present paper

FIG. 1. *Brazil's Legal Amazon region (shaded in inset maplet) with the four existing large dams.*
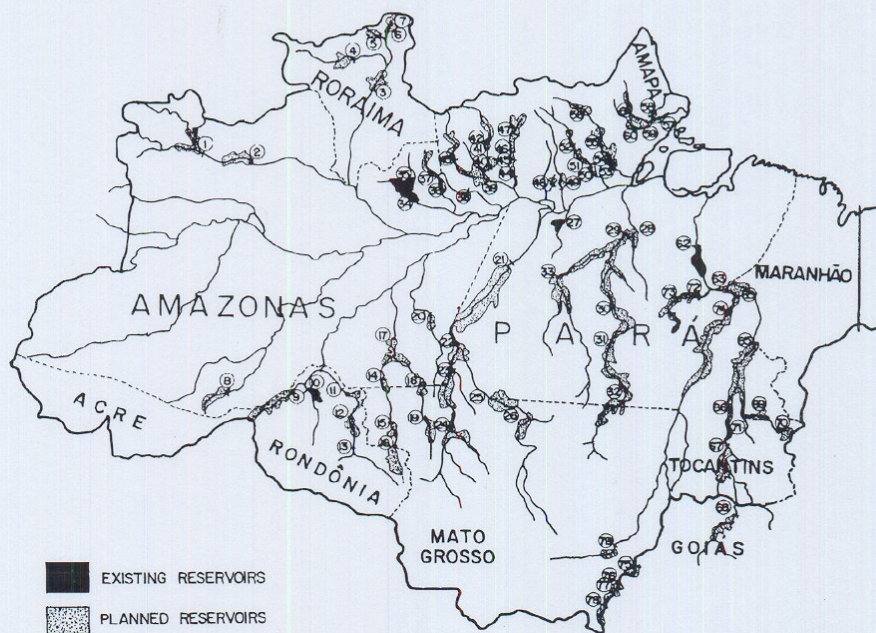

FIG. 2. *Seventy-nine planned and existing dams in Brazilian Amazonia. Only dams in the ELETRONORTE system are included, not those planned by State Governments or private firms. Redrawn from Seva (1990), who based the map on Brazil, ELETROBRÁS (1986) and Brazil, ELETRONORTE (1985c).*

<div align="center">TABLE I</div>

Existing and Planned Dams in Brazilian Amazonia.

Dam Nr	Dam's Name	River Valley	Projected Installed Capacity (MW)
1.	São Gabriel	Uaupés/Negro	2,000
2.	Santa Isabel	Uaupés/Negro	2,000
3.	Caracaraí-Mucajaí	Branco	1,000
4.	Maracá	Uraricoera	500
5.	Surumu	Cotingo	100
6.	Bacarão	Cotingo	200
7.	Santo Antônio	Cotingo	200
8.	Endimari	Ituxi	200
9.	Madeira/Caripiana	Mamoré/Madeira	3,800
10.	Samuel	Jamarí	200
11.	Tabajara-JP-3	Ji-Paraná	400
12.	Jaru-JP-16	Ji-Paraná	300
13.	Ji-Paraná-JP-28	Ji-Paraná	100
14.	Preto RV-6	Roosevelt	300
15.	Muiraquitã RV-27	Roosevelt	200
16.	Roosevelt RV-38	Roosevelt	100
17.	Vila do Carmo AN-26	Aripuanã	700
18.	Jacaretinga AN-18	Aripuanã	200
19.	Aripuanã AN-26	Aripuanã	300
20.	Umiris SR-6	Sucunduri	100
21.	Itaituba	Tapajós	13,000
22.	Barra São Manuel	Tapajós	6,000
23.	Santo Augusto	Juruena	2,000
24.	Barra do Madeira (Juruena)	Juruena	1,000
25.	Barra do Apiacás	Teles Pires	2,000
26.	Talama (Novo Horizonte)	Teles Pires	1,000
27.	Curuá-Una	Curuá-Una	100
28.	Belo Monte (Cararaô)	Xingu	8,400
29.	Babaquara	Xingu	6,300
30.	Ipixuna	Xingu	2,300
31.	Kokraimoro	Xingu	1,900
32.	Jarina	Xingu	600
33.	Iriri	Iriri	900
34.	Balbina	Uatumã	300
35.	Fumaça	Uatumã	100
36.	Onça	Jatapu	300
37.	Katuema	Jatapu	300
38.	Nhamundá/Mapuera	Nhamundá	200
39.	Cachoeira Porteira	Trombetas	1,400
40.	Tajá	Trombetas	300
41.	Maria José	Trombetas	200
42.	Treze Quedas	Trombetas	200
43.	Carona	(Trombetas)	300
44.	Carapanã	Erepecuru	600
45.	Mel	Erepecuru	500
46.	Armazém	Erepecuru	400
47.	Paciência	Erepecuru	300
48.	Curuá	Curuá	100
49.	Maecuru	Maecuru	100
50.	Paru III	Paru	200
51.	Paru II	Paru	200
52.	Paru I	Paru	100
53.	Jari IV	Jari	300
54.	Jari III	Jari	500
55.	Jari II	Jari	200
56.	Jari I	Jari	100
57.	F. Gomes	Araguari	100
58.	Paredão	Araguari	200
59.	Caldeirão	Araguari	200
60.	Arrependido	Araguari	200
61.	Santo Antônio	Araguari	100
62.	Tucuruí	Tocantins	6,600
63.	Marabá	Tocantins	3,900
64.	Santo Antônio	Tocantins	1,400
65.	Carolina	Tocantins	1,200
66.	Lajeado	Tocantins	800
67.	Ipueiras	Tocantins	500
68.	São Felix	Tocantins	1,200
69.	Sono II	Sono	200
70.	Sono I	Sono	100
71.	Balsas I	Balsas	100
72.	Itacaiúnas II	Itacaiúnas	200
73.	Itacaiúnas I	Itacaiúnas	100
74.	Santa Isabel	Araguaia	2,200
75.	Barra do Caiapó	Araguaia	200
76.	Torixoréu	Araguaia	200
77.	Barra do Peixe	Araguaia	300
78.	Couto de Magalhães	Araguaia	200
79.	Noidori	Mortes	100
		Total:	85,900

[a] Based on list derived from ELETRONORTE sources by Seva (1990, pp. 26–7). Dam numbers correspond to numbering in Fig. 2.

assesses the amounts, types, and vertical distribution, of biomass in areas flooded by reservoirs. Rough inferences are drawn as to emissions resulting from decay of this biomass; but the certainty that can be attached to them is low, due to poor understanding of rates and pathways of decay for flooded biomass. Hydroelectric emissions are the least well-understood of 'greenhouse' gas emissions from Amazonian deforestation (hydroelectric flooding is considered to be a form of deforestation [*cf.* Fearnside, 1993]).

The ultimate contribution of hydroelectric flooding to atmospheric carbon is much easier to calculate than the impact of this flooding on the annual balance of emissions, that requires knowledge of the rates of decay and of the proportions of carbon emitted as carbon dioxide (CO_2) and methane (CH_4), the latter of which is some eleven times as effective as the former in 'greenhouse' warming per unit of weight. The ultimate contribution of dams to carbon emissions is the difference between the carbon stock in the forest prior to flooding and that in the reservoir when once the forest has decayed and an equilibrium is reached. Reservoirs in tropical forest areas have a much greater potential for 'greenhouse' gas emissions than do reservoirs in low-biomass landscapes that characterize most of the world's existing hydroelectric dams. The amount of power generated also strongly affects the comparative impacts of hydroelectric *versus* fossil-fuel generation.

In Amazonia, dams are frequently worse than petroleum from the point of view of the ultimate total of 'greenhouse' gas emissions. The worst case is the Balbina Dam. Junk & Mello (1987) calculated that it would take 114 years of fossil-fuel burning to equal the carbon emissions of the flooded forest in Balbina. The calculation made by those Authors considered Balbina's installed capacity of 250 megawatts (MW) and an area of 1,650 km².

The installed capacity of a dam represents what would be generated if all turbines were to operate year-around. Because the flow of the Uatumã River at Balbina is only sufficient to run all the turbines for a fraction of the year, output at the dam averages 112 MW, and losses in transmission to Manaus reduce the average delivered to 109 MW (Brazil, ELETRONORTE/MONASA/ENGE-RIO, 1976). The area of the reservoir used by Junk & Mello (1987) was apparently chosen from preliminary estimates that foresaw an area considerably smaller than do more recent estimates. Considering the average power delivered to Manaus and the 'official' reservoir area of 2,360 km² at the normal maximum operating level of 50 m elevation above mean sea-level, Fearnside (1989) amended to 250

years Junk & Mello's estimate of the time that petroleum would need to be burned to equal Balbina's ultimate emissions of carbon.

While useful as an illustration, calculation of the ultimate contribution to carbon emissions tells us little about the contribution to the annual balance of emissions. The United Nations Framework Convention on Climate Change (UN-FCCC), signed at the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro in June 1992 by 155 countries *plus* the European Union, stipulates that each nation must make an inventory of carbon stocks and fluxes of 'greenhouse' gases. This implies that the annual balance of 'greenhouse' gas fluxes will be the criterion adopted for assigning responsibility among nations for global warming. Because forest biomass in Amazonian reservoirs decays exceedingly slowly, the contribution to the *annual* balance is very different from the ultimate potential for emitting carbon.

In addition to the timing of emissions, the amount that is emitted as methane rather than carbon dioxide strongly influences the global warming impact of reservoirs. Per ton of carbon, methane is much more potent than carbon dioxide in provoking the 'greenhouse' effect. The average lifetime of methane in the atmosphere is much shorter than that of carbon dioxide: 10.5 years *versus* 120 years, given a constant-composition atmosphere as assumed by the Intergovernmental Panel for Climate Change (IPCC) (Isaksen *et al.*, 1992 p. 56). Different methods of calculating global warming equivalence of the various 'greenhouse' gases result in widely varying values for the importance of methane; those methods that consider indirect effects and those that give emphasis to impacts in the near future assign substantially more weight to methane.

The IPCC's preferred method of calculation in its 1992 Supplementary Report considers a 100-years' time-horizon without discounting, and only considers direct effects (Isaksen *et al.*, 1992 p. 56). This assigns to each ton of methane gas a weight 11 times greater than each ton of carbon dioxide. If indirect effects are considered when using the same time-horizon, as was done in the IPCC's 1990 report (Shine *et al.*, 1990 p. 60), the weight given to methane relative to CO_2 (in respect of global warming potential) is 21. Because much of methane's global warming impact is through indirect effects, the current state of disagreement over an appropriate global warming potential for methane is likely to be resolved in favour of higher values, thereby increasing the relative importance of impacts from Amazonian hydroelectric reservoirs.

The Amazonian *várzea* (white-water floodplain) has been identified as one of the world's major sources of atmospheric methane (Mooney *et al.*, 1987). The *várzea* occupies about 2% of the 5×10^6 km² Legal Amazon, the same percentage that would be flooded if all of the 100,000 km² of reservoirs planned for the region are created (Brazil, ELETROBRÁS, 1987 p. 150). Virtually all planned hydroelectric dams are in the forested portion of the region, of which they would represent approximately 2.5–2.9% of the total area. Were these reservoirs to contribute an output of methane per km² of the same order as that produced by the *várzea*, they would together represent a significant contribution to the global 'greenhouse' effect. This methane source would be a virtually permanent addition to 'greenhouse' gas fluxes, rather than a one-time input in the manner of the CO_2 releases from forest decay.

AN APPROACH TO CALCULATING EMISSIONS FROM RESERVOIRS

In order to calculate emissions from hydroelectric reservoirs, one must know the amounts of biomass present and the likely paths by which it will decay. The trees left standing in the reservoir are obviously an important component. The portion of the tree projecting out of the water can be assumed to decay through processes similar to those affecting trees in clearings for agriculture and ranching, with part of the biomass being ingested by termites (which emit a small amount of methane), and part decomposing through other forms of decay which, in the aerobic environment above the water, produce only CO_2. The biomass above the water-level eventually falls into the water, thereby being transferred to the anoxic environments where decay is much slower — but also more likely to yield methane. The leaves and 'vines' (climbers, etc.) fall off the trees very quickly, and the branches and trunks fall at a much slower rate. With them, of course, will fall any remaining epiphytes.

The reservoir can be divided into different zones, where aerobic and anoxic conditions will be of different relative importance. Part of the reservoir is alternately exposed and flooded as water levels fluctuate between the minimum and maximum normal operating levels. All biomass components in this zone, including litter and below-ground biomass, will be exposed to aerobic conditions at some time during the year. The portion of standing trunks in the permanently flooded zone that are located between the minimum and maximum normal operating levels will also be exposed to aerobic conditions and have different relative importance (Fig. 3).

For underwater biomass, the part near the surface will be in an environment that has some oxygen. The anoxic zone does not correspond directly to the hypolimnion, and for purposes of decay is even closer to the water's surface. At Balbina, for example, although a very small amount of oxygen is measurable as deep down as 5 m (G.V. Peña, pers. comm. 1993), persons interested in commercial exploitation of flooded timber consider any wood below 1 m to be unaffected by decay (E.V.C. Monteiro de Paula, pers. comm. 1993).

Decay in the anoxic-water zone is exceedingly slow, even for leaves that are generally believed to decay rapidly. ELETRONORTE commissioned the Delft Hydraulics Laboratory in Delft, The Netherlands, to produce a model for water quality in Balbina (Brazil, ELETRONORTE, 1987*a* p. 261). The model, known as OXY-STRATIF, assumes that all leaves, litter, and fine branches, will decay within ten years. However, more than five years after filling Balbina, much of this material is still present (although no quantitative information is available). The very slow nature of decay in the anoxic zone is illustrated by bundles of leaves that were placed at a depth of 5 m for studies of insects and other organisms in Balbina: after ten months the visual appearance of the leaves remained as green as the day when they were placed in the water. No macroscopic organisms colonized the leaves, and not even the slime that typically forms on decaying material was present (G.V. Peña, pers. comm. 1993).

In shallow areas of the reservoirs, methane bubbling is easily observed. At both Balbina and Tucuruí, bubbles can be seen everywhere — even when no pressure is exerted, as by stepping on the bottom. The nature of the
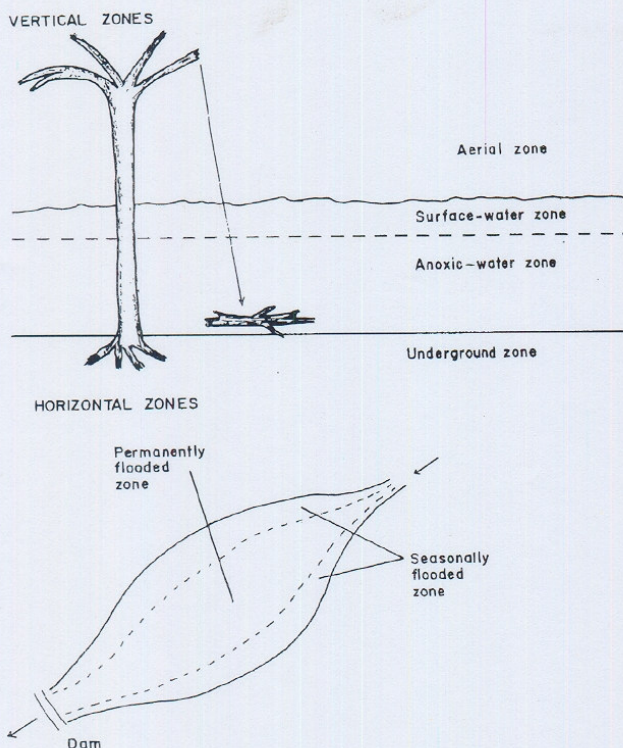
ZONES FOR DISTRIBUTION OF BIOMASS IN RESERVOIRS

FIG. 3. *Zones for designating distribution of biomass in reservoirs.*

environment — devoid of oxygen, with relatively high temperatures and high levels of nutrients — makes it ideal for methane-producing decay processes.

Emissions from decaying forest biomass will be supplemented from decay of organic matter which enters the reservoir from rivers and streams that feed it, from soil organic matter, and from macrophytes that grow in the reservoir. The production of methane from these sources must be considered. In the case of macrophytes, which remove CO_2 from the atmosphere as they grow, the CO_2 released when they decay need not be considered as a net addition (with the exception of any soil organic matter oxidized). Data on methane production from these sources, which may be loosely described as production from the water itself, are not available for any Amazonian reservoir, the closest available surrogate being natural lakes in the *várzea*.

Methane production from decomposition is not strictly identical with methane emission to the atmosphere, as some of the methane dissolved in the water column will instead be oxidized to CO_2 before entering the atmosphere. Because of the limited amount of mixing through the thermocline, high concentrations of methane in the water in the hypolimnion will only enter the atmosphere as the water passes through the turbines; at that point, great quantities of methane can be expected to be released, due to the abrupt reduction in pressure. This occurs, for example, in water passing through turbines in reservoirs in Canada (M. Lucotte, pers. comm. 1993). However, not all methane will be exposed to the atmosphere in the

reservoir and at the turbines; some will occur downstream of the dam. The dissolved concentration of CH_4 in the water released from the turbines or over the spillway is an important measurement that needs to be made, but not all the CH_4 present in these water-flows can be considered as methane emissions — some CH_4 may be oxidized to CO_2 in the river (Rosa, 1992).

Methane-rich water from the hypolimnion is occasionally released in reservoirs in central and western Amazonia (*e.g.* at Balbina and Samuel) when a cold wave (*friagem*) reduces surface temperatures and causes dissolution of the thermocline (the barrier created by thermal stratification of the water column that prevents vertical mixing) resulting in a turnover in the water. Many fish die during these events — for example in April 1993 at Balbina. Such events are more frequent in the western part of Amazonia, and are not a factor in the eastern part of the region, where most planned reservoirs would be located.

'GREENHOUSE' GAS EMISSIONS

Parameters for Emissions' Calculations

Estimating emissions from reservoirs first requires estimates of the area of forest to be flooded in each impoundment. The river-bed area within each reservoir must be estimated and subtracted from the water-surface area. River-bed areas are calculated in Table II from estimates of the length and average width of the rivers. The surface areas of the reservoirs were measured from Landsat-TM 1:250,000-scale images (Fearnside *et al.*, in prep.). Previously deforested areas and river-bed areas are deducted when forest loss is calculated (Table III).

Vertical distribution of biomass, and classification into trunks, leaves, and other components, is important for determining what portion of the biomass will decay above the water and what will decay underwater in the permanently flooded and seasonally flooded zones. The only existing biomass study that assigns the biomass to vertical strata in the region is that of Klinge & Rodrigues (1973), done at INPA's Reserva Egler, 64 km east of Manaus. The approximate dry-weights are given in Table IV. The forest at the Reserva Egler has a maximum height of 38.1 m, which must be assumed to apply to the forests in the four existing large reservoirs.

Biomass estimates specific for each reservoir are available for all except Curuá-Una (*cf.* Table V). Fortunately, the forest flooded at Curuá-Una has an area of only 65 km^2, representing only 1.3% of the total 4,824 km^2 of forest flooded by 1990 in the region (*cf.* Table V). Biomass for Curuá-Una is assumed to be the average estimated for all areas deforested in the 1989–90 period (Fearnside, in prep. *a*). Based on the proportion in vertical strata (*cf.* Table IV), the water depths at minimum and maximum operating levels (*cf.* Table V), and the areas in each zone (*ibid.*), the biomass is calculated for each reservoir in the following categories: above-water zone wood, surface-water zone wood, anoxic-water zone leaves and other non-wood (all assumed to fall to the bottom of the reservoir), and below-ground wood (*cf.* Table V). The amounts of wood removed by logging prior to filling and after filling (through AD 1990) are also roughly estimated (*ibid.*).

After these calculations, the progression of biomass

TABLE II

River-bed Areas in Amazonian Reservoirs.

Reservoir	River	Length in reservoir (km)[a]	Average width (m)[b]	River-bed area (km^2)	Source
Balbina	Uatumã	210	139	29	
	Pitinga	100	99	10	
				Total: 39	c
Curuá-Una	Curuá-Una	80	69	6	
	Muju	40	35	1	
	Mojui dos Campos	20	15	0	
				Total: 7	d
Samuel	Jamari	255	116	29	e
Tucuruí	Tocantins	170	1891	321	f
Total				397	

a Lengths of Balbina and Tucuruí from Juras (1988).
b River widths measured at approximately 5-km intervals using the following maps or images indicated under Source at the following scales: Balbina: 1:100,000; Samuel: 1:40,000; Tucuruí: 1:250,000. Widths of Curuá-Una and tributaries are based on 6 direct measurements by Robertson (1980).
c Brazil, ELETRONORTE, 1985a.
d Robertson, 1980.
e Brazil, ELETRONORTE, not dated a.
f Brazil, Projeto RADAMBRASIL, 1981.

TABLE III

Flooding by Hydroelectric Dams.

Dam	State	Dates of filling	Previous deforest-ation in flooded area (km^2)	River-bed area (km^2)[a]	Official area of water surface (km^2)[b]	Landsat-measured water surface area in 1989 (km^2)[c]	Estimated forest loss (km^2)[d]	1988–1989 forest loss rate (km^2 yr^{-1})
1	2	3	4	5	6	7	8	9
Balbina	Amazonas	1 Oct. 1987–15 July 1989	55	39	2,360	3,147	3,108	693[e]
Curuá-Una	Pará	Jan. 1977–May 1977	0	7	102	72	65[f]	0
Samuel	Rondônia	Oct. 1988–July 1989	91	29	645	465	436	436
Tucuruí	Pará	6 Sept. 1984–30 Mar. 1985	400[g]	321	2,430	2,247	1,926	0
Total			546	397	5,537	5,931	5,534	1,129

a Balbina river-bed area estimates from Brazil, ELETRONORTE (1985a) 1:100,000 scale map; Curuá-Una river-bed area calculated from map and river width measurements of Robertson (1980); Samuel river-bed area estimated from length; Tucuruí river-bed area from Brazil, Projeto RADAMBRASIL, 1981.
b Official areas for comparison only. Sources: Balbina: Brazil, ELETRONORTE, 1987a; Curuá-Una: Robertson, 1980 p. 9; Samuel: Cardenas, 1986; Tucuruí: Brazil, ELETRONORTE [1987] pp. 24–5.
c Three small dams outside the ELETRONORTE system are: Pitinga (filled in 1982 and raised in 1993, 1989 Landsat-measured area = 62 km^2) near Balbina in Amazonas, Boa Esperança (filled prior to 1989[b], Landsat-measured area = 24 km^2) in Maranhão, and Jatapu (filled in 1994, official area = 45 km^2) in Roraima. All of the area flooded by these dams represents forest loss. The two dams filled prior to 1989 would bring the Landsat-measured total area to 6,017 km^2 and the estimated forest loss to 5,620 km^2.
d Landsat-measured water surface includes river-bed and previous deforestation. To avoid double counting, estimated forest loss does not include previous deforestation: Column 8 = Column 7 − Column 5. (Source: Fearnside et al., in prep.).
e Balbina 1988–89 rate is an overestimate due to lack of a 1988 image (230/61) covering approximately 10–20% of the reservoir area nearest to the dam. If unimaged area represented 10% of the measured 1988 area, then Balbina loss rate in 1988–89 was 348 km^2 yr^{-1} (a decrease of 34%); if 20%, then loss rate was 162 km^2 yr^{-1} (a 70% decrease).
f Area measured by Robertson (1980) from Centrais Elétricas do Para (CELPA) map. Paiva (1977) gives the official area as 86 km^2.
g Area cleared by ELETRONORTE only (Brazil, ELETRONORTE, [1987b]).

values is calculated for each year for each reservoir, zone, and biomass component. This is done by using rates of decay in each zone and rates of biomass falling from the above-water to the below-water zones; these rates and other parameters for emission calculations are given in Table VI. The resulting biomass distributions in 1990 are given in Table VII.

The decay rates for underwater biomass are known to be exceedingly slow, but actual measurements are com-pletely lacking. The average lifetimes assumed here are: 50 years for wood in the surface-water zone, 200 years for leaves in the anoxic-water zone, 500 years for wood in the anoxic-water zone, 500 years for below-ground biomass in the permanently flooded zone, and 50 years for below-ground biomass in the seasonally flooded zone (cf. Table VI).

Methane is also produced from ongoing biological processes that are independent of the stock of original

TABLE IV

Biomass by Stratum near Manaus: Approximate Dry-weights [a].

Stratum	Mean Height (m)[b]		Approximate Dry-weight Biomass (t ha-1)					Percent of Total Above-ground Biomass				
	Midpoint	Range (±)	Leaves	Stems	Branches	Total live wood	Total live biomass	Leaves	Stems	Branches	Total live wood	Total live biomass
A	29.6	5.9	1.1	66.1	23.1	89.3	90.3	0.28	17.15	6.00	23.14	23.43
B	21.1	4.4	3.4	127.9	58.5	186.4	189.8	0.87	33.17	15.16	48.33	49.21
C1	11.5	3.1	1.9	22.5	12.4	34.9	36.7	0.48	5.83	3.21	9.04	9.52
C2	4.8	1.2	1.0	4.8	1.7	6.5	7.4	0.25	1.23	0.44	1.68	1.92
D	2.4	0.7	1.0	0.9	0.3	1.2	2.2	0.27	0.22	0.09	0.31	0.58
E	0.6	0.5	0.3	0.4	0.0	0.4	0.7	0.07	0.10	0.00	0.10	0.17
			8.6	222.5	96.0	318.5	327.1	2.23	57.69	24.91	82.60	84.83
'Vines' (climbers, etc.)			21.9					5.67				
Epiphytes			0.1					0.03				
Totals for non-wood, wood, and all live above-ground biomass			30.6			318.5	349.1	7.92			82.60	90.52
Fine litter[c]			10.9					2.83				
Downed dead wood[d]						18.02					4.67	
Standing dead wood[d]						7.6					1.97	
Totals for non-wood, wood, and all above-ground biomass			41.5			344.2	385.6	10.76			89.24	100.00

[a] Data for fresh-weights from Klinge & Rodrigues (1973), converted to dry-weights using a constant correction factor of 0.475 derived for these data by the same authors (Klinge *et al.*, 1975).
[b] Maximum height of the stand was 38.1 m. The stand is located 64 km east of Manaus at INPA's Reserva Egler.
[c] Average of 5 measurements at hydroelectric dam sites at Samuel, Belo Monte, and Babaquara (Cardenas, 1987, 1988; Martinelli *et al.*, 1988).
[d] Klinge, 1973 p. 179.

forest biomass. These include decomposition of organic matter entering the reservoir concerned from a river, and from decay of macrophytes that grow on a portion of the reservoir's surface. These rates are assumed to be equal to those that have been found for open water and for macrophyte beds in studies of natural *várzea* lakes (Table VIII). Only methane is considered from these sources, as the carbon dioxide that they also generate is recycled when the macrophytes and other plants regrow. Chemical characteristics of water in the Balbina reservoir, for example (located on a black-water river), differ in a number of ways from white-water *várzea* lakes, making clear the importance of direct measurements of methane production in reservoirs.

Simulation of Emissions over Time

The 'greenhouse' gas fluxes by process in 1990 are presented in Table IX. While information on emissions from all sources at a given time, such as in 1990, is needed as a baseline for assessing changes in 'greenhouse' gas emissions, the evolution of emissions over time is important for evaluating potential impacts of planned projects. The timing of emissions is also very important in any system of emissions' evaluation that gives differential weight to short-term and long-term impacts, as by discounting.

The emissions of CO_2 and CH_4 from Balbina are simulated for 50 years after closing in Fig. 4. Methane emissions are fairly constant over the entire period, but carbon dioxide emissions are concentrated in a tremendous pulse in the first decade after closing. As of 1994, approximately half of the total CO_2 emission from Balbina had taken place, according to the simulation reported here.
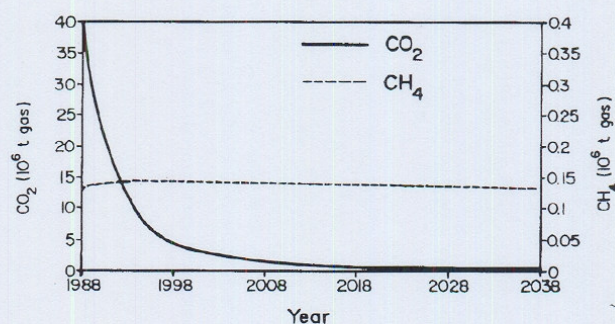
FIG. 4. *Balbina: CO_2 and CH_4 emissions (million t of gas).*

The global warming impact of emissions can be converted to CO_2-equivalent carbon using global warming potentials adopted by the Intergovernmental Panel on Climate Change (IPCC) for direct effects only, over a 100-years time-horizon without discounting (Isaksen *et al.*, 1992). This is an underestimate of the true impact of reservoirs, as at least half of the global warming provoked by methane is through indirect rather than direct effects. In Fig. 5 the CO_2-equivalent carbon of the emissions is simulated for 50 years for the four existing large reservoirs in Brazilian Amazonia.

Comparison with Fossil-fuel Emissions

Comparisons of emissions from hydroelectric projects with the emissions avoided from generating the same amount of power from fossil fuels are important because of the frequency with which hydroelectric projects have been promoted as offering a 'clean' alternative to thermoelectric

TABLE V

Biomass Present and Division by Zones in Amazonian Reservoirs.

Dam	Year filled	Water surface area at operating level (ha)	Forest flooded at operating level (ha)	Forest flooded at minimum level (ha)	Approximate total biomass (t ha⁻¹)	Above-ground biomass (t ha⁻¹)	Biomass source	Average depth at minimum level (m)	Depth source
Balbina	1987	314,700	310,840	206,829	441	336	[a], pp. 172–3	6.2	[a], p. 14
Curuá-Una	1977	7,200	6,480	5,500	428	327	Fearnside, in prep. [a]	6.2	[b]
Samuel	1988	46,500	43,551	30,901	557	425	[c], p. 4	5.3	[b]
Tucuruí	1984	224,700	192,553	106,787	517	394	[d]	9.7	[e]
Totals		593,100	553,424	350,017					

Dam	Initial biomass by zone (t dry matter ha⁻¹)					
	Above-water wood	Surface-water wood	Anoxic-water wood and other non-wood	Anoxic-water leaves	Below-ground wood	Total
Balbina	264.69	4.55	31.44	35.70	104.74	441.12
Curuá-Una	257.11	4.42	30.54	34.68	101.74	428.50
Samuel	339.59	5.74	34.56	45.11	132.34	557.34
Tucuruí	291.40	5.33	55.47	41.82	122.69	516.71

Dam	Logging removals of biomass (t ha⁻¹ of reservoir area)		Fraction of above-ground wood removed before filling	Fraction of original anoxic-zone wood removed after filling	Years of post-filling logging activity		Area cleared prior to filling (ha)			Draw-down depth (m)	Draw-down depth source
	Before filling	After filling			Begin	End	Season-ally flooded zone	Perma-nently flooded zone	Total		
Balbina	0		0	0.5	1993	2000	0	5,000	5,000	4	
Curuá-Una	0	0	0	0						4.5	guess
Samuel			0.2	0						7	[f], p. 5
Tucuruí			0.01	0.5	1988	2000	2,000	8,000	10,000	14	[g], p. 5

[a] Brazil, ELETRONORTE, 1987a; forest flooded at minimum level is adjusted by ratio of Landsat-measured area to official area at the operating level.

[b] Paiva, 1977 p. 17 (value for average depth at maximum operating level).

[c] Cardenas & Amaral, 1986; forest area flooded at minimum water level taken as proportional to water volumes at these two levels from Brazil, ELETRONORTE, 1992b p. 5.

[d] Cardenas et al., 1982.

[e] Uses 58 m above mean sea-level as minimum normal operating level (Brazil, ELETRONORTE, c. 1983). A minimum operating level of 51.6 m (Brazil ELETRONORTE, 1992a, 1992b) implies drawdown depth of only 3.3 m. Forest area flooded at minimum water-level is taken as proportional to water volumes at these two levels from Brazil, ELETRONORTE, c. 1983 p. 6.

[f] Brazil, ELETRONORTE, 1992a.
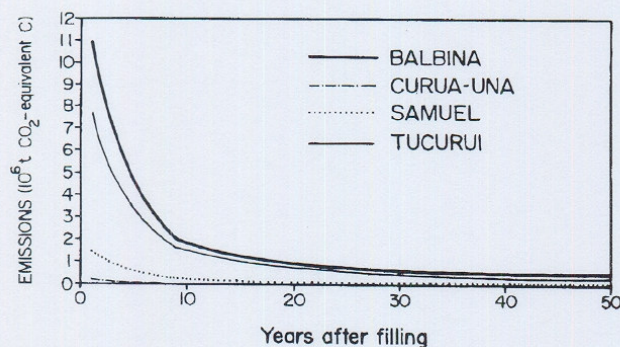
[g] Brazil, ELETRONORTE, 1992b.

FIG. 5. *Hydroelectric 'greenhouse' gas emissions (CO₂-equivalent carbon).*

generation. The examples of Balbina and Tucuruí are given in Table X. The mix of diesel and fuel-oil burned at thermoelectric plants in Manaus (the city served by Balbina) is assumed to apply also to avoided emissions from Tucuruí. Emissions factors for these fuels applying to thermoelectric plants in Canada are assumed to apply to Brazil (probably an optimistic assumption). Power from Balbina substitutes for approximately 1.3 million t of CO_2-equivalent carbon (*see* Table X, part F), far less than the emission of 6.9 million t from decaying biomass in the reservoir (Table XI). Table XI also compares 1990 emissions of Balbina and Tucuruí with emissions from other sources.

These Amazonian reservoirs compare poorly with two reservoirs in Canada that have been identified as sources of 'greenhouse' gases (Rudd et al., 1993). The comparative impact of Balbina and Tucuruí is even worse than

TABLE VI

Parameters for Hydroelectric Dam Emission Calculations.

Parameter	Value	Units	Source
Above-ground fraction	0.773		Fearnside, in prep. *a*
Average depth of surface-water zone	1	metre	Assumption, based on commercial timber spoilage
Leaf decay rate in seasonally inundated zone	−0.5	Fraction yr^{-1}	Assumption
Above-water decay rate (0–4 yrs)	−0.1691	Fraction yr^{-1}	Assumed same as felled forest (Fearnside, in prep. *b*)
Above-water decay rate (5–7 yrs)	−0.1841	Fraction yr^{-1}	Assumed same as felled forest (Fearnside, in prep. *b*)
Above-water decay rate (8–10 yrs)	−0.0848	Fraction yr^{-1}	Assumed same as felled forest (Fearnside, in prep. *b*)
Above-water decay rate (> 10 yrs)	−0.0987	Fraction yr^{-1}	Assumed same as felled forest (Fearnside, in prep. *b*)
Fraction of above-water decay *via* termites	0.0844	Fraction	Assumed same as felled forest (Martius *et al.*, in prep.)
Wood decay rate in surface-water zone	−0.0139	Fraction yr^{-1}	Assumption: average lifetime = 50 years
Leaf decay rate in anoxic-water zone	−0.0035	Fraction yr^{-1}	Assumption: average lifetime = 200 years
Wood decay rate in anoxic-water zone	−0.0014	Fraction yr^{-1}	Assumption: average lifetime = 500 years
Below-ground decay rate in permanently flooded zone	−0.0014	Fraction yr^{-1}	Assumption: average lifetime = 500 years
Below-ground decay rate in seasonally flooded zone	−0.0139	Fraction yr^{-1}	Assumption: average lifetime = 50 years
Fraction of C released as CH_4 in termite decay	0.002		Calculated from measurement by Martius *et al.*, 1993 for *Nasutitermes macrocephalus* (a *várzea* species)
Fraction of C released as CH_4 in termite decay (high trace-gas scenario)	0.0079		Calculated from measurement by Martius *et al.*, 1993 for *Nasutitermes macrocephalus* (a *várzea* species)
Fraction of C released as CH_4 in surface-water zone decay	0		Assumption
Fraction of C released as CH_4 in anoxic-water zone decay	1		Assumption
Fraction of C released as CH_4 in below-ground decay	1		Assumption
Fraction of water covered by macrophytes	0.1		Assumption
Methane release from macrophyte beds	174.67	µg m^{-2} day^{-1}	Table VIII
Methane release from open water	53.93	µg m^{-2} day^{-1}	Table VIII
Carbon content of wood	0.50		Fearnside *et al.*, 1993
Carbon content of leaves and fine litter	0.45		Assumption
Carbon content of 'vines' (climbers, etc.) and epiphytes	0.45		Assumption
Rate of wood-fall from above-water zone	0.1155	Fraction yr^{-1}	Assumption: average lifetime = 6 years
Fraction of CH_4 oxidized in water	0		Assumption
Leaf aerobic decay, first year	0.025	Fraction of original leaf biomass lost annually	Calculated from Brazil, ELETRONORTE, 1987*b* p. 261 (OXY-STRATIF model parameter for Balbina). Value divided by 10 (as a guess at the exaggeration in OXY-STRATIF)
Leaf aerobic decay, after first year	0.0085	Fraction of original leaf biomass lost annually	Calculated from Brazil, ELETRONORTE, 1987*b* p. 261. Value divided by 10 (as a guess at the exaggeration in OXY-STRATIF)

Biomass of Components in Unlogged Original Forests

Parameter	Value	Units	Source
Average total biomass of forest	428	t ha^{-1}	
Average water-depth at minimum level	10	metres	Assumption
Initial biomass present: leaves	7.30	t ha^{-1}	Calculated from total biomass and Table IV.
Initial biomass present: fine litter	8.75	t ha^{-1}	Calculated from total biomass and Table IV.
Initial biomass present: 'vines' (climbers, etc.) and epiphytes	18.64	t ha^{-1}	Calculated from total biomass and Table IV.
Initial biomass present: wood above water	240.33	t ha^{-1}	Calculated from total biomass and Table IV.
Initial biomass present: wood in surface zone	4.42	t ha^{-1}	Calculated from total biomass and Table IV.
Initial biomass present: wood in anoxic zone	47.32	t ha^{-1}	Calculated from total biomass and Table IV.
Initial biomass present: below-ground	101.74	t ha^{-1}	Calculated from total biomass and Table IV.

these emissions' estimates indicate, because the Canadian study used a global warming potential (GWP) for calculating the CO_2 equivalent of methane which was over five times as high as the IPCC GWP used in the present paper. By converting emissions to CO_2 carbon equivalents and using the same IPCC GWPs used in the current calculation, Rosa & Schaeffer (1994) have shown that the Canadian reservoirs studied by Rudd *et al.* (1993) have less global-warming impact than would generating the same amount of energy from fossil fuel.

In Fig. 6 the emissions of Balbina are simulated over 50 years, in comparison with the emissions that would be produced by supplying the same energy to Manaus from fossil fuels. The tremendous disadvantage of hydroelec-
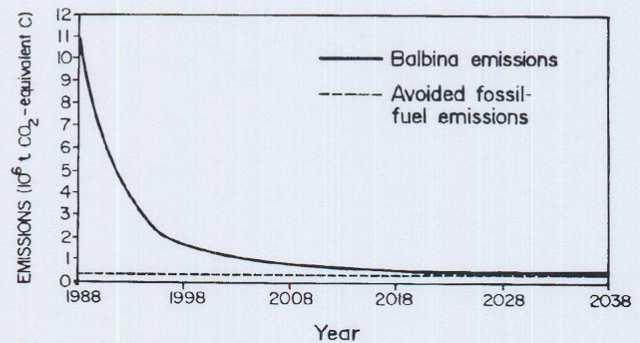

FIG. 6. *Balbina: 'Greenhouse' gas emissions (CO_2-equivalent carbon).*

TABLE VII

Approximate Quantities of Biomass Present in 1990 (10^6 t of biomass).

Permanently Flooded Zone (at minimum operating water-level)

	Above-water wood	Surface-water wood	Anoxic-water wood	Anoxic-water leaves and other non-wood	Below-ground wood	Total
Balbina	28.85	0.89	20.50	7.09	27.19	84.52
Curuá-Una	0.04	0.02	0.84	0.15	0.51	1.56
Samuel	6.17	0.11	2.17	1.07	3.04	12.57
Tucuruí	6.00	0.41	13.01	3.52	10.46	33.41
Totals	41.06	1.44	36.52	11.84	41.20	132.05

Seasonally Flooded Zone (at maximum normal operating water-level)

	Above-water wood	Leaves and other non-wood	Under-water wood	Below-ground wood	Total
Balbina	19.61	2.02	2.41	10.11	34.14
Curuá-Una	0.04	0.00	0.01	0.08	0.13
Samuel	2.77	0.42	0.46	1.57	5.22
Tucuruí	7.47	0.78	6.35	9.54	24.14
Totals	29.88	3.22	9.23	21.30	63.64

TABLE VIII

Methane Emissions from Amazon Floodplain Ecosystems.

Habitat	Methane flux (mg CH_4 m^{-2} day^{-1})			Lago da Machantaria (near Manaus)			NASA/ABLE rising water	Value assumed for Amazonian reservoirs
	Low water CAMREX cruise 11	High water CAMREX cruise 9	Eight lakes near Manaus	Low water	Rising water	High water		
	(1)	(1)	(1)	(2)	(2)	(2)	(3)	(4)
Lakes, open water	40 (± 12)	88 (± 30)	58 (± 16)	50-100	5-50	5-25	74 (± 14)	53.9
Lakes, macrophyte beds	131 (± 47)	390 (± 109)	251 (± 58)	dry	0-50	0-100	201 (± 35)	174.7
Lakes, flooded forest	7.1 (± 3.4)	74 (± 19)	55 (± 13)	dry	0-200	0-200	126 (± 20)	

Sources:
(1) Devol *et al.*, 1990.
(2) Wassmann & Thein, 1989.
(3) Bartlett *et al.*, 1990.
(4) For comparison, Aselmann & Crutzen (1990 p. 446) estimate the average for lakes of the world to be 43 mg CH_4 m^{-2} day^{-1}.

tric generation in the initial years is evident. In the case of Balbina (which has a very large area per unit of electricity generated), even after 50 years (and probably for an indefinite period), the emissions will continue to exceed those from fossil fuels. These results indeed call into question the image of Amazonian hydroelectric dams as helping to reduce global warming!

CONCLUSIONS

Hydroelectric reservoirs in Brazilian Amazonia emitted, very approximately, 0.26 million tons of CH_4 gas and 38 million tons of CO_2 gas in 1990. Of the CH_4, approximately 0.11 million tons were emitted from open water, 0.04 from macrophyte beds, < 0.01 from above-water decay of forest biomass, and 0.11 million tons from underwater decay of forest biomass. The underwater decay rates are the least reliable of these estimates. No net carbon dioxide emissions come from open water or macrophytes. Above-water decay contributed approximately 99% of the estimated 38 million tons of CO_2 emitted. Using 1992 IPCC global warming potentials, these emissions are equivalent to approximately 11 million tons of CO_2-equivalent carbon.

The total area of planned reservoirs in Brazilian Amazonia is approximately 20 times the area which was present in 1990, implying a potential annual emission rate of about 5.2 million tons of methane. While the methane emission represents an essentially permanent addition to gas fluxes to the atmosphere, the carbon dioxide is released in a tremendous pulse during the first decade

TABLE IX

'Greenhouse Gas' Fluxes by Process in 1990 from Hydroelectric Dams[a].

Permanently Inundated Zone

	Area of permanently inundated zone (ha)	Above-water decay			Underwater decay						Below-ground decay	
		Termites		Wood in surface-Other	Wood in surface-water-zone		Wood in anoxic-water zone		Leaves and other non-wood biomass			
		CH_4 (10^6 t gas)	CO_2 (10^6 t gas)	CO_2 (10^6 t gas)	CH_4 (10^6 t gas)	CO_2 (10^6 t gas)	CH_4 (10^6 t gas)	CO_2 (10^6 t gas)	CH_4 (10^6 t gas)	CO_2 (10^6 t gas)	CH_4 (10^6 t gas)	CO_2 (10^6 t gas)
Balbina	206,829	0.00	0.28	8.61	0.00	0.02	0.02	0.00	0.01	0.10	0.03	0.00
Curuá-Una	5,500	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Samuel	30,901	0.00	0.06	1.84	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00
Tucuruí	106,787	0.00	0.06	1.98	0.00	0.01	0.01	0.00	0.01	0.05	0.01	0.00
Totals	350,017	0.00	0.41	12.43	0.00	0.04	0.03	0.00	0.02	0.20	0.04	0.00

Seasonally Inundated Zone

	Area of seasonally inundated zone (ha)	Above-water decay		Underwater decay			Leaves and other non-wood biomass		Below-ground decay	
		Termites		Other	Wood					
		CH_4 (10^6 t gas)	CO_2 (10^6 t gas)	CO_2 (10^6 t gas)	CH_4 (10^6 t gas)	CO_2 (10^6 t gas)	CH_4 (10^6 t gas)	CO_2 (10^6 t gas)	CH_4 (10^6 t gas)	CO_2 (10^6 t gas)
Balbina	104,011	0.0004	0.46	14.22	0.002	0.000	0.005	0.05	0.00007	0.00
Curuá-Una	980	0.0000	0.00	0.03	0.000	0.000	0.000	0.00	0.00000	0.00
Samuel	12,650	0.0001	0.07	2.16	0.000	0.000	0.001	0.02	0.00001	0.00
Tucuruí	85,766	0.0002	0.23	7.06	0.006	0.000	0.002	0.05	0.00006	0.00
Totals	203,407	0.0006	0.77	23.47	0.009	0.000	0.007	0.13	0.00014	0.00

Entire Reservoir

	Area of reservoir at operating level (ha)	Open water CH_4 (10^6 t gas)	Macrophyte beds CH_4 (10^6 t gas)	Total from above-water decay		Total from underwater decay		Total CH_4 (10^6 t gas)	Total CO_2 (10^6 t gas)	CO_2-equivalent carbon (100-yr, zero discount direct effects) (10^6 t carbon)
				CH_4 (10^6 t gas)	CO_2 (10^6 t gas)	CH_4 (10^6 t gas)	CO_2 (10^6 t gas)			
Balbina	314,700	0.06	0.02	0.00	23.58	0.07	0.18	0.14	23.75	6.91
Curuá-Una	7,200	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.03	0.02
Samuel	46,500	0.01	0.00	0.00	4.13	0.01	0.07	0.02	4.20	1.21
Tucuruí	224,700	0.04	0.01	0.00	9.34	0.04	0.11	0.09	9.45	2.85
Totals	593,100	0.11	0.04	0.00	37.07	0.12	0.36	0.26	37.44	10.99

[a] These results use the 'low trace-gas scenario' emission factor for termites. Using the 'high' value (based on Gorean & Mello, 1987) increases the total emission only marginally from 0.259 to 0.260 X 10^6 t of methane gas.

after dam-closure. These CO_2 emissions greatly exceed the avoided emissions from fossil-fuel combustion.

SUMMARY

Existing hydroelectric dams in Brazilian Amazonia emitted about 0.26 million tons of methane and 38 million tons of carbon dioxide in 1990. The methane emissions represent an essentially permanent addition to gas fluxes from the region, rather than a one-time release. The total area of reservoirs planned in the region is about 20 times the area existing in 1990, implying a potential annual methane release of about 5.2 million tons. About 40% of this estimated release is from underwater decay of forest biomass, which is the most uncertain of the components in the calculation. Methane is also released in significant quantities from open water, macrophyte beds, and above-water decay of forest biomass.*

Hydroelectric dams release a large pulse of carbon dioxide from above-water decay of trees left standing in

*In answer to our query the Author responded (*in litt.*) 'Cattle do release a substantial amount of methane, but humans don't release it directly (they do release it through landfills, etc., of course). I once queried some of the methane inventory people at the US-EPA about the omission of humans from the 'animal' sources and was told that human flatulence is almost pure hydrogen.

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TABLE X

Calculation of Emissions from Fossil Fuels Displaced by Balbina and Tucuruí.

</div>

A) DAM CHARACTERISTICS

	Units	Balbina (1993)	Tucuruí (1991)	Sources Balbina	Tucuruí
Installed capacity*	MW	250	4000		
Installed capacity*	TWh yr^{-1}	2.19	35.06		
Average generation	MW	110.3	2057	a	
Average generation	TWh yr^{-1}	0.97	18.03		b
Percentage of capacity	(%)	44.1	51.4		

* The amount that would be generated if all of the turbines operated all of the time — something that never happens, as the amount of water is insufficient for this. The turbines must also stop operating occasionally for repairs.

B) MANAUS POWER AND FUEL USE

	Units	Amounts	Source
Power consumption in 1986	TWh	0.94	
Projected substitution for 1993:			
Diesel	10^6 l	316	
Diesel	GWh	791	
Fuel oil	10^3 t	113	
Fuel oil	GWh	333	
Total:	TWh	1.12	c

C) EMISSION FACTORS FOR FUELS

Fuel   Emission factor (t gas per 10^6 l) [d]

Fuel	CO$_2$	CH$_4$	N$_2$O
Diesel	2,730	0.12 (0.06-0.25)	0.16 (0.13-0.4)
Light oil	2,830	0.02 (0.01-0.21)	0.16 (0.13-0.4)
Heavy oil	3,090	0.13 (0.03-0.12)	0.16 (0.13-0.4)

D) BALBINA FOSSIL FUEL SUBSTITUTION (OFFICIAL PROJECTION FOR 1993)

Fuel	Million litres	Density (t m^{-3}) [e]	Million tons	Avoided emissions (t gas) CO$_2$	CH$_4$	N$_2$O
Diesel	316	0.87	275	862,680	38	51
Fuel oil [f]	122	0.93	113	375,452	15	20
Total			388	1,238,132	53	71

E) GLOBAL WARMING POTENTIALS OF GASES

	CO$_2$	CH$_4$	N$_2$O
Global warming potential [g]	1	11	270

F) CO$_2$-GAS EQUIVALENTS OF FUELS DISPLACED BY BALBINA

Fuel   CO$_2$-gas equivalent (t)

Fuel	CO$_2$	CH$_4$	N$_2$O	Total
Diesel	862,680	417	13,865	876,962
Fuel oil	375,452	167	5,331	380,950
Total	1,238,132	584	19,196	1,257,911

Notes:
[a] Brazil, ELETRONORTE, 1985b. Note: Brazil, ELETRONORTE/MONASA/ENGE-RIO, 1976 gives average generation as 109 MW (= 0.96 TWh yr^{-1}).
[b] Brazil, ELETRONORTE, 1992a, p. 3.
[c] Brazil, ELETRONORTE, 1985b: Quadro 3.7.
[d] Jaques, 1992.
[e] Jaques, 1992 p. 48.
[f] Assumed to be heavy fuel-oil.
[g] Radiative forcing, per t of gas, relative to 1 t of CO^2, over a 100-yrs time-horizon without discounting (Isaksen *et al.*, 1992 p. 56).

TABLE XI

Comparison of Balbina and Tucuruí 1990 Hydroelectric Generating Emissions with Other Emissions Sources.

Emission source	Hydro. annual emission (CO_2-C equiv.) (t)	Hydro./ fossil fuel emission ratio	Emission/generation		Note
			10^6 t CO_2-equiv./ TWh	10^6 t CO_2-equiv. C/ TWh	
Balbina	6,908,399	20.1	26.20	7.14	
Tucuruí	2,852,731	0.4	0.58	0.16	a
Manaus fossil fuel			1.30	0.35	
Coal-fired			0.4	0.11	b, c
Natural gas			1.0	0.27	b
Churchill/Nelson Dam (Canada)			0.04–0.06	0.01	b
Grand Rapids Dam (Canada)			0.30–0.5	0.11	b, c

[a] Assumes that fossil-fuel mix substituted by Tucuruí is the same as that used in Manaus.

[b] Comparisons from Rudd *et al.*, 1993 (N.B.: these Authors use a value of 60 for the global warming potential of methane — much higher than the IPCC value of 11 used for Balbina and Tucuruí).

[c] Uses mid-point.

the reservoirs, especially during the first decade after closing. This elevates the expected global warming impact of the dams to levels much higher than would occur by generating the same power from fossil fuels. In 1990, the impoundment behind the Balbina Dam (closed in 1987) had over 20 times more impact on expectable global warming than would generating the same power from fossil fuels, while the Tucuruí Dam (closed in 1984) had 0.4 times the impact of fossil fuels. Because of the large area flooded per unit of electricity generated at Balbina, 'greenhouse' gas emissions are expected to exceed avoided fossil-fuel emissions indefinitely.

REFERENCES

ASELMANN, I. & CRUTZEN, P.J. (1990). A global inventory of wetland distribution and seasonality, net productivity, and estimated methane emissions. Pp. 441–9 in *Soils and the Greenhouse Effect* (Ed. A.F. BOUWMAN). Wiley, New York, NY, USA: 575 pp., illustr.

BARTLETT, K.B., CRILL, P.M., BONASSI, J.A., RICHEY, J.E. & HARRISS, R.C. (1990). Methane flux from the Amazon River floodplain: Emissions during rising water. *J. Geophysical Research*, **95**(D10), pp. 16,773–8.

BRAZIL, ELETROBRÁS (1986). *Plano de Recuperação Setorial*. Ministério das Minas e Energia, Centrais Elétricas do Brasil (ELETROBRÁS), Brasília, Brazil: [not available for checking].

BRAZIL, ELETROBRÁS (1987). *Plano 2010: Relatório Geral. Plano Nacional de Energia Elétrica 1987/2010 (dezembro de 1987)*. Ministério das Minas e Energia, Centrais Elétricas do Brasil (ELETROBRÁS), Brasília, Brazil: 269 pp., illustr.

BRAZIL, ELETRONORTE (1985a). *Aproveitamento Hidrelétrico de Balbina: Reservatório — N.A. 50 m*. Centrais Elétricas do Norte do Brasil, SA (ELETRONORTE), Balbina, Amazonas, Brazil: Map scale: 1:100,000.

BRAZIL, ELETRONORTE (1985b). *UHE Balbina e Atendimento do Mercado Energético de Manaus, Junho/85, Relatório 26.657*. Centrais Elétricas do Norte do Brasil, SA (ELETRONORTE), Brasília, Brazil [not available for checking].

BRAZIL, ELETRONORTE (1985c). Políticas e Estratégias para Implementação de Vilas Residenciais. Centrais Elétricas do Norte do Brasil, SA (ELETRONORTE), Brasília, Brazil: map.

BRAZIL, ELETRONORTE (1987a). *Estudos Ambientais do Reservatório de Balbina. Relatório "diagnóstico" BAL-50-1001-RE*. Centrais Elétricas do Norte do Brasil, SA (ELETRONORTE), Brasília, Brazil: 308 pp.

BRAZIL, ELETRONORTE [1987b]. *Livro Branco sobre o Meio Ambiente da Usina Hidrelétrica de Tucuruí*. Centrais Elétricas do Norte do Brasil, SA (ELETRONORTE), Brasília, Brazil: 288 pp., illustr.

BRAZIL, ELETRONORTE (1992a). *Ambiente Desenvolvimento Tucuruí*. Centrais Elétricas do Norte do Brasil, SA (ELETRONORTE), Brasília, Brazil: 32 pp., illustr.

BRAZIL, ELETRONORTE (1992b). *Ambiente Desenvolvimento Samuel*. Centrais Elétricas do Norte do Brasil, SA (ELETRONORTE), Brasília, Brazil: 24 pp., illustr.

BRAZIL, ELETRONORTE (no dated a). Reservatório da UHE Samuel: Levantamento Planimétrico. Centrais Elétricas do Norte do Brasil, SA (ELETRONORTE), Brasília, Brazil: map scale: 1:40,000.

BRAZIL, ELETRONORTE (no dated b). *UHE Tucuruí: Plano de Utilização do Reservatório, Caracterização e Diagnóstico do Reservatório e de sua Área de Influência*. TUC-10-263-46-RE Volume I — Texto. Centrais Elétricas do Norte do Brasil, SA (ELETRONORTE), Brasília, Brazil: [irregular pagination].

BRAZIL, ELETRONORTE [c. 1983]. *Usina Hidrelétrica Tucuruí 8.000 MW*. Centrais Elétricas do Norte do Brasil, SA (ELETRONORTE), Brasília, Brazil: 27 pp., illustr.

BRAZIL, ELETRONORTE/MONASA/ENGE-RIO (1976). *Estudos Amazônia, Relatório Final Volume IV: Aproveitamento Hidrelétrico do Rio Uatumã em Cachoeira Balbina, Estudos de Viabilidade*. Centrais Elétricas do Norte do Brasil (ELETRONORTE)/MONASA Consultoria e Projetos Ltda./ENGE-RIO Engenharia e Consultoria, SA, Brasília, Brazil: [irregular pagination], illustr.

BRAZIL, PROJETO RADAMBRASIL (1981). *Mosaico Semi-controlado de Radar*. Map Scale: 1:250,000. Folhas SA-22-ZC, SB-22-XA, SB-22-XB, and SB-22-SD. Departamento Nacional de Produção Mineral (DNPM), Rio de Janeiro, Brazil.

CARDENAS, J.D. REVILLA (1986). *Estudos de ecologia e controle ambiental na região do reservatório da UHE de Samuel. Convênio: ELN/MCT/CNPq/INPA de 01.07.82. Relatório Setorial, Segmento: Estimativa da Fitomassa. Período julho– dezembro 1986*. Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, Amazonas, Brazil: 194 pp.

CARDENAS, J.D. REVILLA (1987). *Relatório: Levantamento e Análise da Fitomassa da UHE de Kararaô, Rio Xingú*. Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, Amazonas, Brazil: 181 pp., illustr.

CARDENAS, J.D. REVILLA (1988). *Relatório: Levantamento e Análise da Fitomassa da UHE de Babaquara, Rio Xingú*. Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, Amazonas, Brazil: 277 pp., illustr.

CARDENAS, J.D. REVILLA & AMARAL, I.L. DO (1986). *Estudos de Ecologia e Controle Ambiental na Região do Reservatório da UHE de Samuel: Convênio ELN/CNPq/INPA, de 01.07.82. Relatório Setorial, Segmento Minhocucus, Período janeiro/junho 1986*. Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, Amazonas, Brazil: 5 pp.

CARDENAS, J.D. REVILLA, KAHN, F.L. & GUILLAMET, J.L. (1982). Estimativa da fitomassa do reservatório da UHE de Tucuruí. Pp. 1–11 in *Projeto Tucuruí, Relatório Semestral, Período janeiro/ junho 1982, Vol. 2: Limnologia, Macrófitas, Fitomassa, Degra-*

dação da Fitomassa, Doenças Endêmicas, Solos. Brazil, Centrais Elétricas do Norte do Brasil, SA (ELETRONORTE) & Instituto Nacional de Pesquisas da Amazônia (INPA). INPA, Manaus, Amazonas, Brazil: 32 pp.

DEVOL, A.H., RICHEY, J.H., FORSBERG, B.R. & MARTINELLI, L.A. (1990). Seasonal dynamics in methane emissions from the Amazon River floodplain to the troposphere. *J. Geophysical Research*, **95**(D10), pp. 16, 417–26, 5 figs.

FEARNSIDE, P.M. (1989). Brazil's Balbina Dam: Environment *versus* the legacy of the pharaohs in Amazonia. *Environmental Management*, **13**(4), pp. 401–23, 5 figs.

FEARNSIDE, P.M. (1993). Deforestation in Brazilian Amazonia: The effect of population and land tenure. *Ambio*, **22**(8), pp. 537–45, 4 figs.

FEARNSIDE, P.M. (in prep. *a*). *Biomass of Brazil's Amazonian Forests.*

FEARNSIDE, P.M. (in prep. *b*). *Amazonia and Global Warming: Annual Balance of Greenhouse Gas Emissions from Land-use Change in Brazil's Amazon Region.*

FEARNSIDE, P.M., LEAL FILHO, N. & FERNANDES, P.M. (1993). Rainforest burning and the global carbon budget: biomass, combustion efficiency and charcoal formation in the Brazilian Amazon. *J. Geophysical Research*, **98**(D9), pp. 16, 733–43, 6 figs.

FEARNSIDE, P.M., MEIRA FILHO, L.G. & TARDIN, A.T. (in prep.) *Deforestation Rate in Brazilian Amazonia.*

GOREAU, T.J. & MELLO, W.Z. (1987). 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. Pp. 51–66 in *Proceedings of the Workshop on Biogeochemistry of Tropical Rain Forests: Problems for Research* (Eds D. ATHIÉ, T.E. LOVEJOY & P. de M. OYENS). Universidade de São Paulo, Centro de Energia Nuclear na Agricultura (CENA), Piracicaba, São Paulo, Brazil: 85 pp., illustr.

ISAKSEN, I.S.A., RAMASWAMY, V., RODHE, H. & WIGLEY, T.M.L. (1992). Radiative forcing of climate. Pp. 47–67 in *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment* (Eds J.T. HOUGHTON, B.A. CALLANDER & S.K. VARNEY). Cambridge University Press, Cambridge, England, UK: 200 pp.

JAQUES, A.P. (1992). *Canada's Greenhouse Gas Emissions: Estimates for 1990.* Report EPS 5/AP/4. Environment Canada, Ottawa, Ontario, Canada: 78 pp.

JUNK, W.J. & MELLO, J.A. NUNES DE (1987). Impactos ecológicos das represas hidrelétricas na bacia amazônica brasileira. Pp. 367–85 in *Homem e Natureza na Amazônia* (Ed. G. KOHLHEPP & A. SCHRADER). (*Tübinger Geographische Studien 95* [Tübinger Beiträge zur Geographischen Lateinamerika-Forschung 3].) Geographisches Institut, Universität Tübingen, Tübingen, Germany: iii + 507 pp., illustr.

JURAS, A.A. (1988). *Programa de Estudos da Ictiofauna na Área de Atuação das Centrais Elétricas do Norte do Brasil, SA* (ELETRONORTE). ELETRONORTE, Brasília, Brazil: 48 pp. + annexes.

KLINGE, H. (1973). Biomasa y materia orgánica del suelo en el ecosistema de la pluviselva centro-amazónico. *Acta Científica Venezolana*, **24**(5), pp. 174–81.

KLINGE, H. & RODRIGUES, W.A. (1973). Biomass estimation in a central Amazonian rain forest. *Acta Científica Venezolana*, **24**(5), pp. 225–37.

KLINGE, H., RODRIGUES, W.A., BRUNIG, E. & FITTKAU, E.J. (1975). Biomass and structure in a Central Amazonian rain forest. Pp. 115–22 in *Tropical Ecological Systems: Trends in Terrestrial and Aquatic Research* (Eds F. GOLLEY & E. MEDINA). Springer-Verlag, New York, NY, USA: 398 pp., illustr.

MARTINELLI, L.A., VICTORIA, R.L., MOREIRA, M.Z., ARRUDA JR., G., BROWN, I.F., FERREIRA, C.A.C., COELHO, L.F., LIMA, R.P. & THOMAS, W.W. (1988). *Implantação de parcelas para monitoreamento de dinâmica florestal na área de proteção ambiental, UHE Samuel, Rondônia: Relatório preliminar.* Centro de Energia Nuclear na Agricultura (CENA), Piracicaba, São Paulo, Brazil: (unpublished report: 72 pp.).

MARTIUS, C., FEARNSIDE, P.M., WASSMANN, R. & BANDEIRA, A.G. (in prep.). *Deforestation and Methane Release from Termites in Amazonia.*

MARTIUS, C., WASSMANN, R., THEIN, U., BANDEIRA, A.G., RENNENBERG, H., JUNK, W. & SEILER, W. (1993). Methane emission from wood-feeding termites in Amazonia. *Chemosphere*, **26**(1–4), pp. 623–32.

MOONEY, H.A., VITOUSEK, P.M. & MATSON, P.A. (1987). Exchange of materials between terrestrial ecosystems and the atmosphere. *Science*, **238**, pp. 926–32.

PAIVA, M.P. (1977). *The Environmental Impact of Man-made Lakes in the Amazonian Region of Brazil.* Centrais Elétricas Brasileiras, SA (ELETROBRÁS), Diretoria de Coordenação, Rio de Janeiro, Brazil: 69 pp.

ROBERTSON, B.A. (1980). *Composição, Abundância e Distribuição de Cladocera (Crustacea) na Região de Água Livre da Represa de Curuá-Una, Pará.* Masters thesis, Fundação Universidadedo Amazonas (FUA) & Instituto Nacional de Pesquisas da Amazônia (INPA). INPA, Manaus, Amazonas, Brazil: 105 pp.

ROSA, L.P. (1992). [Untitled presentation at the] *INPE/OECD Workshop on Inventories of Nat Anthropogenic Emissions of Greenhouse Gases*, São José dos Campos, São Paulo, Brazil, 9–11 March 1992 [not available for checking].

ROSA, L.P. & SCHAEFFER, R. (1994). Greenhouse gas emissions from hydroelectric reservoirs. *Ambio*, **23**(2), pp. 164–5.

RUDD, J.W.M., HARRIS, R., KELLY, C.A. & HECKY, R.E. (1993). Are hydroelectric reservoirs significant sources of greenhouse gases? *Ambio*, **22**(4), pp. 246–8, fig.

SEVA, O. (1990). Works on the Great Bend of the Xingu — a historic trauma? Pp. 19-35 in *Hydroelectric Dams on Brazil's Xingu River and Indigenous Peoples* (Eds L.A. de O. SANTOS & L.M.M. de ANDRADE). (Cultural Survival Report 30.) Cultural Survival, Cambridge, Massachusetts, USA: 192 pp., illustr.

SHINE, K.P., DERWENT, R.G., WUEBBLES, D.J. & MORCRETTE, J.-J. (1990). Radiative forcing of climate. Pp. 41–68 in *Climate Change: The IPCC Scientific Assessment* (Eds J.T. HOUGHTON, G.J. JENKINS & J.J. EPHRAUMS). Cambridge University Press, Cambridge, England, UK: 365 pp.

WASSMANN, R. & THEIN, U.G. (1989). *Spatial and Seasonal Variation of Methane Emission from an Amazon Floodplain Lake.* Paper presented at the Workshop on 'Cycling of Reduced Gases in the Hydrosphere', SIL Congress, Munich, Germany, 17 August 1989: (manuscript, 8 pp.).