DO HYDROELECTRIC DAMS MITIGATE GLOBAL WARMING? THE CASE OF BRAZIL'S CURUÁ-UNA DAM

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Abstract. Hydroelectric dams in tropical forest areas emit greenhouse gases, as illustrated by the Curuá-Una Dam in the Amazonian portion of Brazil. Emissions include carbon dioxide from decay of the above-water portions of trees that are left standing in the reservoir and methane from soft vegetation that decays under anaerobic conditions on the bottom of the reservoir, especially macrophytes (water weeds) and vegetation that grows in the drawdown zone and is flooded when the reservoir water level rises. Some methane is released from the reservoir surface through bubbling and diffusion, but larger amounts are released from water passing through the turbines and spillway. Methane concentration in the water increases with depth, and the turbines and spillway draw water from sufficient depth to have substantial methane content. In 1990 (13 years after filling), the Curuá-Una Dam emitted 3.6 times more greenhouse gases than would have been emitted by generating the same amount of electricity from oil.

Keywords: Amazonia, Brazil, dams, greenhouse gas emissions, hydroelectric dams, reservoirs

1. Introduction

Greenhouse-gas emissions represent an important environmental concern regarding hydroelectric dam construction in tropical forest areas. The 40-MW Curuá-Una Dam, located 70 km SW of Santarém at Cachoeira de Palhão (2° 50'S, 54° 18'W) on the Curuá-Una River in Brazil's Amazonian state of Pará (Fig. 1), provides an example of a number of features of tropical dams that can result in high emissions of greenhouse gases. Most (57.4%) of the reservoir is in the Curuá-Una River valley, but parts of it occupy tributary valleys of the Rivers Moju (11.7%), Mojuí (4.4%) and Poraquê (3.2%), plus several small streams (2.9%) (Vieira 1982, p. 13). The reservoir filled from January to May 1977, and occupies 72 km^2 at its normal operating level of 68 m above mean sea level (msl) (Table I). The present paper calculates the greenhouse-gas impact of the dam based on information on streamflow, water management, the configuration of the dam and information adapted from a variety of sources to estimate greenhouse-gas releases. Methane emissions from turbines and spillways are calculated based on concentration profiles and annual cycles at similar dams, surface emissions of methane (CH_4) are derived from available flux measurements at Curuá-Una, while carbon dioxide (CO_2) emissions from above-water decay are derived from decay rates in cleared forest. Estimated emissions are compared to what would have been emitted if the same amount of electricity had been generated from fossil fuels in 1990, which is the standard base year for national inventories of greenhouse gases under the United Nations Framework Convention on Climate Change. The net emission in 1990 (age 13 years) is expected to be stable over the long term. By 1990 CO_2 emission from above-water decay had already declined to only 10% of the annual total emission; this 10% would decline to zero in later years. The present analysis finds much higher emissions than some have suggested, and provides a direct comparison with Brazil's official estimates from the preliminary National Inventory of Greenhouse Gas-Emissions.

[Figure 1 here]
[Table I here]

The present paper focuses on tropical dams. Dams in other regions can also produce emissions; the amount of emission for non-tropical dams is usually less than for tropical dams, although existing studies are generally confined to estimates of surface emissions (see: St-Louis et al. 2000, Duchemin et al. 2002). In non-tropical cases where there is a substantial drawdown, large emissions are found even in older dams. A case in point is the Três Marias Dam, in a savanna area in the Brazilian state of Minas Gerais, with a 9-m vertical drawdown, where surface emissions alone give the dam a greater impact than fossil fuels 36 years after dam construction (see emissions data in: Rosa et al. 2002, 2004).

2. Carbon dioxide emissions

Hydroelectric dams produce greenhouse-gas emissions from several sources, and all must be included in order to have valid estimates of the global-warming impact of these projects. Decay of above-water biomass -- the portions of the trees that project above the water surface -- is substantial in the first decade after a reservoir is formed in a tropical forest area, subsequently declining as the biomass stock dwindles. The 7-km^2 riverbed area at Curuá-Una(calculated from a map reproduced by Robertson 1980; see Fearnside 1995, p. 11) must be deducted from the reservoir area in calculating the amount of forest flooded, estimated at 65 km^2. When the wood in standing trees decays, it releases carbon dioxide (CO_2), since half the dry weight of the wood is carbon. The shallow reservoir (average depth 6 m at the normal operating level) and large range of vertical fluctuation (4-6 m) mean that much of the flooded biomass projects out of the water where it can decay under aerobic conditions (Fig. 2). The forest that was flooded is classified as dense ombrophilous lowland forest (Db) (Brazil, IBGE and IBDF 1988), which has an average above-ground biomass of 390 Mg/ha in Pará (Updated from Fearnside 1994, 1997a, p. 332, including adjustments from Fearnside and Laurance 2004 and Nogueira 2004, Nogueira et al. 2004).

[Figure 2 here]

The rate of decay of the dead trees that project above the water surface is a matter of some uncertainty. The present calculation makes the assumption (optimistic from the point-of-view of emissions in 1990) that decay follows the pattern observed in Amazonian clearings that had been cut for agriculture and ranching (see Barbosa and Fearnside 1996). Under these assumptions, most of the wood that was present when the reservoir was filled would have disappeared by 1990

(13 years after filling). If one assumes a rate of wood fall from the above-water zone into the below-water zones that corresponds to a half-life of six years, together with the above-water decay rates based on decay in clearing for agriculture (as in Fearnside 1995), then only 0.010 million t C was emitted from above-water decay in 1990 (Table II). This appears to be an underestimate because much of the wood that falls is later oxidized under aerobic conditions, either as floating driftwood or during drawdown periods. The possibility that this biomass decays much more slowly has been suggested by Gunkel et al. (2003, p. 211); however, most of the undecayed biomass still present 23 years after flooding appears to be the seasonally flooded portion of each trunk, while almost all of the biomass above the high-water mark had disappeared.

[Table II here]

3. Methane emissions

3.1. CARBON SOURCES

Methane is produced when decomposition takes place under anaerobic conditions at the bottom of a reservoir. The wood in the dead trees is quite resistant to decay under these conditions, but soft green plant matter such as macrophytes (water weeds) and the vegetation that re-grows in the drawdown areas will decay quickly, releasing methane (CH_4). Per ton of gas, CH_4 has 21 times more impact on global warming than CO_2, considering the 100-year time horizon global warming potentials (GWPs) adopted by the Kyoto Protocol (Schimel et al. 1996, p. 121), or 23 times greater considering GWPs of the same type as revised in the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)(Ramaswamy et al. 2001, p. 388). The more conservative value used by the Kyoto Protocol will be adopted in this calculation to facilitate comparison with other estimates, including those in Brazil’s National Inventory.

Curuá-Una has a large drawdown area relative to the size of the reservoir. Normal operation officially has a fluctuation of 4 m between the maximum and minimum operating levels (Table III), but, in practice, the reservoir is drawn down by 6 m in drought years (Duchemin et al. 2000). For comparison, Brazil’s Itaipú reservoir operates on a fluctuation of only 20-40 cm. The large drawdown area (48% of the total reservoir area) is typical of existing ‘large’ (>

10 MW) Amazonian dams, for which this percentage ranges from 40 to 66% (Table III). Curuá-Una is also typical in terms of power density (Watts of installed capacity per square meter of reservoir area); this dam's value of 0.89 W/m^2 representing the median for existing dams (Table III). The large areas of exposed mudflats become veritable methane factories: the soft vegetation that grows there decays under largely anaerobic conditions when it is later flooded. As an indication of the amount of biomass involved, herbaceous vegetation accumulates above-ground dry-weight biomass of 5.7 Mg ha^{-1} (SD=1.7, range=3.2-8.7) during a three-month drawdown in *várzea* (floodplain) near Manaus (Junk and Piedade 1997, p. 170). In Curuá-Una's 34.8 km^2 drawdown zone, this amount of biomass (45% of which is carbon) would represent almost 9000 Mg of carbon annually. Curuá-Una is much smaller, in both area and installed capacity, than other large dams in the region; it serves as a sort of microcosm for the problem of greenhouse-gas emissions from hydroelectric development. As the first 'large' dam constructed in Brazilian Amazonia, Curuá-Una's status as an older dam gives an important perspective to the problem; most other work has been done on much younger dams (e.g., Fearnside 2002a, in press, Galy-Lacaux et al. 1999).

[Table III here]

In addition to carbon from macrophytes and from plants flooded in the drawdown areas, carbon inputs from erosion in the watershed can also supply a source for methane formation. The Curuá-Una watershed has undergone substantial deforestation, resulting in erosion and a "cultural eutrophication" of the reservoir that maintains nutrient concentrations in the water at levels that, although modest, are sufficient to sustain substantial productivity, especially of macrophytes (Gunkel et al. 2003). This productivity can be expected to maintain CH_4 emissions indefinitely, both from the macrophytes and from other primary productivity in the reservoir. Any organism that is large enough to sink to the bottom when it dies can contribute to methane production. The primary long-term carbon source, however, is believed to be drawdown-zone vegetation.

A complete accounting would have to deduct the global warming impact of the CO_2 that would have been released from oxidation of some of this carbon in the absence of the dam. This adjustment would probably be small both because a portion of the carbon would be deposited in sediments rather than released to the atmosphere (not necessarily much less than under the reservoir scenario), and because, per ton of carbon, CH_4 has 7.6 times more impact than CO_2 on global warming (at a GWP for CH_4 of 21 in terms of weight of gas).

3.2. SURFACE EMISSIONS

Surface emissions vary greatly depending on the habitat within the reservoir, high emissions coming from macrophyte beds and standing tree areas, and little emission coming from the river channel. During the first years after filling, a significant portion of the reservoir was covered with macrophytes, especially the water hyacinth *Eichhornia crassipes*, but also including smaller areas of *Salvinia auriculata*, *Ricciocarpus natans*, *Pistia stratiotes*, *Scirpus cubensis* and *Utricularia* spp. (Junk et al. 1981; Vieira 1982, pp. 10-11). Immense carpets of macrophytes were held between the standing dead trees, described as giving the dam an "aspect of desolation" (Vieira 1982, p. 11). By 1999 *Polygonum portosiense* (in the family Polygonaceae) had become the dominant species (Gunkel et al. 2003, p. 209).

The shallow reservoir contributes to methane emissions, since less of the CH_4 released at the bottom in bubbles is oxidized to CO_2 as it rises to the surface through the water column. The surface emissions depend on the area of the water surface. A rough estimate for surface emissions can be made (Table IV) assuming that the area in 1990 was the same as that in 1997-1998 (optimistic, given that the water levels in 1997-1998 would be lower due to the El Niño event at that time).

[Table IV here]

Macrophyte beds (*matupás*) have higher emissions than open water. Macrophyte area can be calculated using the power equation derived by de Lima (2002, p. 47) based on satellite time-series data from the Samuel and Tucuruí reservoirs (eq. 1):

$$Y = 0.2\ X^{-0.5} \qquad \text{(eq. 1)}$$

where:
X = Years since flooding
Y = The fraction of the reservoir covered by macrophytes.

Using equation 1, in 1990 macrophytes covered 5.5% of the reservoir surface. This can be considered to be conservative compared to a much higher projection of macrophyte cover by Gunkel et al. (2003, p. 209), who estimated that approximately 40% of the reservoir would have been covered in 1990, a percentage that would decline to a stable level of 20% in 1999; the projection was made based on data from the first years after Curuá-Una was filled (Junk 1982) and the trajectory followed by macrophyte areas in Lake Kariba in Africa. The lower estimate used here is consistent with the observation of Junk and de Mello (1987) that "only small quantities of macrophytes" remained in the reservoir in 1987, diminishing nutrient content of the water having caused them to decline after covering 26.7% of the reservoir in September 1979 (Junk 1982). A similar pattern occurred at the Balbina reservoir (Walker et al. 1999).

3.3. TURBINE EMISSIONS

Water passed through the turbines can be a major source of methane emissions, as this takes large quantities of water from near the bottom of the reservoir. When the water pressure suddenly drops as the water emerges from the turbines, much of the methane gas dissolved in the water is released (Fearnside 2004). Data from the Petit Saut Dam in French Guiana (Galy-Lacaux et al. 1997, 1999) indicate significant emissions from turbined water in tropical reservoirs.

The reservoir has a sharp oxycline at 6 m depth in both the wet and the dry seasons, although thermal stratification is weak (Duchemin et al. 2000). The intakes for both the turbines and the spillway are well below this depth at the normal operating level (Table I). Methane concentration can be assumed to increase in the anoxic water, as occurs in reservoirs generally (e.g., Rosa et al. 1997, Galy-Lacaux et al. 1999). At Curuá-Una no O_2 is detectable in water below 10 m depth (Gunkel et al. 2003, p. 211). Methane concentration increases with depth in a reservoir's water column below the oxycline: at Tucuruí a concentration of 6.0 mg CH_4/liter of water was measured by J.G. Tundisi at a depth of 30 m in March 1989 (Rosa et al. 1997, p. 42). Water containing such high methane concentration would produce substantial greenhouse gas emissions when released by the turbines, as at the Tucuruí Dam (Fearnside 2002a).

A rough estimate of turbine emissions at Curuá-Una in 1990 can be made by assuming that streamflow was equal to the long-term average of 188.4 m^3/second (calculated from Brazil, CEPEL/ELETROBRÁS 1983, p. 5), and that the turbines operated at their full capacity drawing 52 m^3/s each (Brazil, CEPEL 1983). The depth at the 68 m above msl water level that would apply to most of 1990 would be 17.5 m at the central axis of the turbine intake, and the CH_4 concentration adjusted for the seasonal cycle (following Fearnside 2002a based on the cycle at Petit Saut measured by Galy-Lacaux et al. 1997, 1999) would be 5.9 mg CH_4/liter. The assumption is made that 60% of the methane is released on passing through the turbine, reflecting the fact that the dam lacks an aerating devise that contributes to an emission of 89% at Petit Saut based on the measurements by Galy-Lacaux et al. (1997, 1999, see Fearnside 2002a). Given these assumptions, the turbine emission at Curuá-Una in 1990 totaled 0.071 million t CO_2-C equivalent (Table V).

[Table V here]

3.4. SPILLWAY EMISSIONS

Emissions from the spillway in 1990 can be calculated using the same assumptions as for turbine emissions. The depth to the spillway intake is 10.0 m at the normal operating water level (Table I). The seasonally adjusted CH_4 concentration at this depth is 5.0 mg CH_4/liter. The streamflow passed through the spillway is calculated as the average streamflow minus the amount used by the turbines, with adjustments for direct input of rainfall to the reservoir and for evaporation from the reservoir surface. Assuming that 80% of the CH_4 exported in water passed through the spillway is emitted, the spillways released methane equivalent to 0.057 million t CO_2-C equivalent in 1990 (Table VI).

[Table VI here]

3. Comparison with fossil fuels

The annual emissions for 1990 at Curuá-Una, expressed in CO_2-carbon equivalents, are summarized in Table VII. The 1990 emissions (important because of national accounting under the climate convention) do not include the high emissions in the first year and prior to the beginning of power generation, for example from concrete used in dam construction. Greenhouse-gas emissions decline with time, but still stabilize at a level with significant impact, as shown by the current estimate for emissions in 1990 (13 years after filling). The timing of greenhouse-gas impacts in the early years of a dam is one of the principal differences between hydroelectric dams and fossil fuels in terms of global warming (Fearnside 1997b). How this should be taken into account is one of major ongoing debates on greenhouse-gas accounting, with major implications for decision-making on mitigation policies (see Fearnside 2002b,c; Fearnside et al. 2000). Greater weight given to short-term impacts results in a greater impact of hydroelectric dams relative to fossil fuels.

[Table VII here]

The fossil fuel carbon displaced by Curuá-Una can be calculated based on 806.1 g CO_2 gas equivalent/kWh of electricity generated from oil, the mean of seven studies (range 686-949 g) reviewed by van de Vate (1996). Adjustment must be made for transmission loss to Santarém, which is assumed to be the same as the 3% loss estimated for a similar transmission distance at the Samuel Dam in Rondônia (Brazil, ELETRONORTE nd [*C.* 1987]). Power generated in 1990 is assumed to be the same as that generated from May 2000 to April 2001, which totaled 185,655 MWh (Brazil, ANEEL 2001), assuming May and June 2000 had the same production as July. All four of the Curuá-Una Dam's turbines had been installed by 1990. Given these assumptions, Curuá-Una displaced only 0.040 million t CO_2-equivalent C in 1990--much less than the emission from the dam (Table VII).

Greenhouse gas emissions represent a significant impact of tropical hydroelectric dams that is generally not taken into account when decisions are made on dam construction. Much of the hydroelectric industry still touts dams as "clean" energy devoid of such impacts (See International Rivers Network 2002). While fossil fuel generation is often worse than dams from a global-warming perspective, this is not the case at unfavorable sites such as Curuá-Una.

This differs sharply from the preliminary version of Brazil's national inventory of greenhouse gas emissions (Rosa et al. 2002; see also Rosa et al. 2004). The difference is a function of completeness: the official estimates only include emissions from the surface of the reservoir, which account for just 5.2% of Curuá-Una's total recurrent emissions (Table VII). Gross recurrent emissions include those from the surface, turbines and spillway, but not the large one-time pulse of emission from decay of forest biomass in the first years after reservoir formation. Gross recurrent emissions represents the emissions measure appropriate for dams under the national inventories mandated by the Climate Convention (IPCC 1997). The inventories count forest biomass clearing as a form of deforestation emission for reservoirs filled in the inventory period, while displacement of thermal power will be reflected in the fossil-fuel portion of the inventory.

In assessing the relative impacts of different types of electrical generation, consideration must also be given to the emissions of dams from sources in addition to those falling under the hydroelectric dam category in the national emissions inventories. Most important is CO_2 emission from aerobic decay of dead trees projecting above the water. This is considered to be a form of deforestation and would be accounted for in the case of reservoirs filled during the inventory period. In the case of the Curuá-Una reservoir, which was filled before Brazil's 1988-1994 inventory period, these emissions are not counted in inventory's net committed emissions accounting for deforestation. Larger amounts of above-water decay emissions from Tucuruí (filled September 1984-March 1985) are also uncounted, although those from Samuel (filled from October 1988 to July 1989) and part of those from Balbina (filled in October 1987-July 1989) are counted.

The net impact of dams on global warming includes downward adjustments for pre-dam ecosystem fluxes and for fossil-fuel emissions displaced by the dam's electrical output. A full energy chain analysis (not attempted here) would include additional impact from cement, steel and fossil fuel used in dam construction.

In 1990, Curuá-Una had 3.6 times more impact than the fossil fuel it displaced (Table VII). For comparison, in 1990 the Balbina Dam (age 3 years) emitted 22.6 times more than the fossil fuel it replaced (Fearnside, unpublished), the Samuel Dam (age 2 years) emitted 11.6 times more (Fearnside in press), while the Tucuruí Dam in 1990 (age 6 years) emitted 1.8-2.6 times more, considering emissions of 7.0-10.1 million t C at Tucuruí (Fearnside 2002a), 2.5% transmission loss (assumed equal to Balbina, as in Fearnside 1997b), and the same fossil fuel emissions per unit of power used for Curuá-Una.

4.) Uncertainties

Uncertainty surrounding the numbers is high, especially since values often must be derived from a chain of calculations based on information from other locations. Data are insufficient for a formal estimate of the confidence interval associated with the total emission. The percentage of exported methane released at the turbines is perhaps the greatest uncertainty. The 60% value assumed here is in the middle of the 21.0-89.9% range that was used for high and low scenarios at Tucuruí, based on information from Petit Saut (Fearnside 2002a). If the same range of percentage emission is applied to Curuá-Una, the range for the dam's impact as a multiple of fossil fuel emission is 2.4-4.5. The conclusion that the value of 3.6 derived for this multiple in the present paper is much higher than 1.0, indicating that the hydroelectric emission is greater than that of fossil fuels, is believed to be quite firm. The fact that the study includes all major pathways of greenhouse-gas release (surface, turbines, spillway and above-water biomass decay) makes this estimate much more robust than those that present only a part of the picture, such as surface emissions. The conclusion that substantial emissions from hydroelectric dams can be maintained over the long term also appears to be sound. The results of this analysis indicate the need for better measurements of such features as methane profiles in the water column, downstream methane concentrations, drawdown-zone vegetation biomass, and decay rates in the reservoir.

5. Conclusions

Hydroelectric dams in tropical forest areas can emit substantial amounts of greenhouse gases. Brazil's Curuá-Una Dam provides an example of a dam where emissions are high due to such factors as a large reservoir relative to the power output of the dam, a large drawdown area on which soft vegetation grows quickly (only to be submerged and decompose under anaerobic conditions where methane is formed), and high biomass of trees left standing in the reservoir. At Curuá-Una emissions were greater than the fossil-fuel emission displaced by the power generated by the dam: 3.6 times more impact in 1990 (13 years after filling the reservoir), a level of emission that can be expected to remain stable over the long term.

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FIGURE LEGENDS

Figure 1 – Hydroelectric dams in Brazilian Amazonia.

Figure 2 – Schematic diagram of the Curuá-Una dam and reservoir comparing elevations (above mean sea level) of key features. The horizontal axis is not to scale.

TABLE I
Curuá-Una technical parameters.

Parameter	Value	Units	Source
Reservoir area at normal operating level[(a)]	72	km^2	Fearnside 1995, p. 11.
Reservoir volume	472	million m^3	Brazil, CEPEL/ELETROBRÁS 1983, p. 4.
Average depth of reservoir	6	m	Duchemin et al. 2000.
Installed capacity	40	MW	Brazil, CELPA, nd [*C.* 1975].
Retention time	29	days	Duchemin et al. 2000.
Spillway sill level	58.0	m above msl	Brazil, CELPA, nd [*C.* 1975].
Reservoir max normal level	68.0	m above msl	Brazil, CELPA, nd [*C.* 1975].
Reservoir min normal level	64.0	m above msl	Brazil, CELPA, nd [*C.* 1975].
Turbine intake sill level	48.0	m above msl	Brazil, CELPA, nd [*C.* 1975].
Turbine intake top level	52.9	m above msl	Brazil, CELPA, nd [*C.* 1975].
Turbine intake central axis level	50.5	m above msl	Brazil, CELPA, nd [*C.* 1975].

[(a)] This LANDSAT area is considered conservative; the reservoir area has also been reported as 78 km^2 (Brazil, CEPEL/ELETROBRÁS 1983, p. 4), 102 km^2 (Robertson 1980) and 86 km^2 (Paiva 1977, p. 17).

TABLE II
Parameters for the Curuá-Una reservoir emission from above-water biomass.

Parameter	Value	Units	Source
Above-ground fraction	0.759	Fraction	Fearnside 1997b, p. 337
Average depth of surface water zone	1	meter	Assumption, based on commercial timber spoilage
Leaf decay rate in seasonally inundated zone	-0.5	Fraction/yr	Assumption; note seasonal drying accelerates rate: Polunin 1984, p. 129.
Above-water decay rate (0-4 yrs)	-0.1680	Fraction/yr	Assumed same as felled forest (Fearnside 1996, p. 611)
Above-water decay rate (5-7 yrs)	-0.1841	Fraction/yr	Assumed same as felled forest (Fearnside 1996, p. 611)
Above-water decay rate (8-10 yrs)	-0.0848	Fraction/yr	Assumed same as felled forest (Fearnside 1996, p. 611)
Above-water decay rate (>10 yrs)	-0.0987	Fraction/yr	Assumed same as felled forest (Fearnside 1996, p. 611)
Carbon content of wood	0.50		Fearnside et al. 1993)
Rate of wood fall from above-water zone	0.1155	Fraction/yr	Assumption: average lifetime = 6 years.
Average total biomass of forest at Curuá-Una	514	Mg/ha	Updated from Fearnside 1997a[(a)]
Average water depth at minimum level	6.8	meters	Uses 64.0 m above mean sea level as minimum normal operating level (CELPA nd. [*C.* 1975]).
Initial biomass present: leaves	8.7	Mg/ha	Calculated from total biomass and Fearnside (1995, p. 12).
Initial biomass present: wood above water	244.3	Mg/ha	Calculated from total biomass and Fearnside (1995, p. 12).
Initial biomass present: below ground	124.0	Mg/ha	Calculated from total biomass and above-ground fraction.
Methane release by termites	0.687	kg CH_4/ha/yr	Martius et al. 1996, p. 527.

(a) -6.4% from adjustments for form factor (-15.6%) and hollow trees (+9.2%)(Fearnside and Laurance 2004), and -5.7% for wood density (Nogueira et al. 2004, updated from Nogueira 2004).

TABLE III
Comparison of dams in Brazilian Amazonia.

Dam	Area at maximum normal water level (km^2)	Area at minimum normal water level (km^2)	Average depth (m)	Maximum depth (m)	Maximum normal oper-ating level (m)	Minimum normal oper-ating level (m)	Verti-cal Draw-down (m)	Draw-down area (km^2)	Draw-down area as percent of total area (%)	Installed capacity (MW)	Power density (W/m^2)	Drainage area (km^2)	Average Stream-flow (m^3/s)	Reservo volume (billic m^3)
Curuá-Una	72	37	6.2	19.5	68	64	4	35	48	64	0.89	15,300	188	0.
Balbina[(a)]	3,147	1,540	9.2	27.5	51	46	5	1,607	51	250	0.08	18,862	657	11.
Tucurui-I	2,430	1,429	18.8	70.0	72	60	12	1,001	41	3,960	1.63	758,000	11,051	45.
Tucurui-II[(b)]	2,635	950	19.1	72.0	74	51.6	22	1,685	64	8,400	3.19	758,000	11,051	50.
Samuel	645	220	5.3	31.0	87	80	7	425	66	216	0.33	15,280	366	4.

(a) Balbina area from LANDSAT (see Fearnside 1995); water level assumed to be 51 m, the de-facto maximum normal operating level.

(b) Tucuruí-II is the expansion of the Tucuruí-I dam, currently underway; maximum and minimum normal water levels (already in effect) are from Walter Fernandes Santos, public presentation, 17 September 2004.

TABLE IV
Surface emissions at Curuá-Una.

Item	Units	Wet season[a]	Dry season[a]	Note
Bubbles	mg $CH_4/m^2/day$	65±100	12±10	(b)
Diffusion	mg $CH_4/m^2/day$	16±45	20±19	(b)
Total	mg $CH_4/m^2/day$	81	32	
Time	Days	212	153	
Area	km^2	54.6	72	
Seasonal total emission	Mg CH_4	937.6	352.5	
Annual total emission	Mg CH_4/year	1290.1		
Global-warming impact	Million Mg C equivalent/yr	0.007		(c)

(a) Wet season October-April; Dry season May-September.
(b) Duchemin et al. 2000 (surface emission measured in 1997-1998).
(c) CO_2-carbon equivalent at global warming potential of 21 for CH_4 (Schimel et al. 1996).

TABLE V
Turbine emissions.

Item	Value	Units	Source
PARAMETERS			
Power generation	185,566	MWh	Brazil, CEPEL/ELETROBRÁS 1983, p. 5.
Water use per turbine	52.0	m^3/s	Brazil, CEPEL/ELETROBRÁS 1983, p. 5.
Capacity per turbine	10	MW	Brazil, CEPEL/ELETROBRÁS 1983, p. 4.
CH_4 concentration at turbine intake	5.9	mg/liter	Adjusted from 6.0 mg/liter measured at Tucuruí Dam (see text).

Proportion of CH_4 released at turbines	0.6		Estimate based on 0.89 value measured at Petit Saut Dam (see text).
CALCULATED VALUES			
Water use per year	3.47	billion m^3	
CH_4 exported through turbines	20,626	Mg CH_4/year	
CH4 emission from turbines	12,375	Mg CH_4/year	
Emission as CO_2-equivalent C	0.071	million Mg C	(a)

(a) CO_2-carbon equivalent at global warming potential of 21 for CH_4 (Schimel et al. 1996).

TABLE VI
Spillway emissions.

Item	Value	Units	Source
PARAMETERS			
Average streamflow	188.38	m^3/s	Calculated from Brazil, CEPEL/ELETROBRÁS 1983, p. 5.
Precipitation	1750	mm/year	Vieira 1982, p. 2.
Evaporation from open water	1548	mm/year	Assumed equal to Tucuruí (Brazil, ELETRONORTE 1989, p. 47).
Evaporation from macrophytes	2.48	multiple of open-water evaporation	Mean of measurements for *Eichhornia crassipes* by Brezny et al. (1973) (1.26) and by Timmer and Weldon (1967, cited by Brezny et al. 1973)(3.7).
CH_4 concentration at spillway intake	5.0	mg/liter	Adjusted from 6.0 mg/liter measured at Tucuruí Dam (see text).
Proportion of CH_4 released at spillway	0.8		Estimate based on 0.89 value measured at Petit Saut Dam (see text).
CALCULATED VALUES			
Precipitation input	0.13	billion	

		m^3/year	
Evaporation from open water	0.11	billion m^3/year	
Evaporation from macrophytes	0.02	billion m^3/year	
Total outflow	5.95	billion m^3/year	
Spillway average flow rate	78,34	m^3/s	
Spillway annual flow	2.47	billion m^3	
Spillway CH_4 export	12,361	Mg CH_4/year	
Spillway CH_4 emission	9,899	Mg CH_4/year	
Emission as CO_2-equivalent C	0.057	million Mg C	(a)

(a) CO_2-carbon equivalent at global warming potential of 21 for CH_4 (Schimel et al. 1996).

Table VII
Annual emissions of greenhouse gases at Curuá-Una in 1990.

Flux source	Annual emission (million Mg CO_2-equivalent C)	Percentage of gross recurrent emission
RECURRENT (INVENTORY) EMISSIONS		
Surface emissions	0.007	5.5
Turbine emissions	0.071	52.5
Spillway emissions	0.057	42.0
Gross recurrent emissions	0.135	100.0
ADDITIONAL (NON-INVENTORY) COMPONENTS OF NET IMPACT		
Forest biomass aerobic decay	0.010	

Pre-dam ecosystem fluxes[a]	-0.003
NET EMISSION EXCLUSIVE OF FOSSIL FUEL DISPLACEMENT	0.142
Displaced fossil fuels	-0.040
NET EMISSION WITH FOSSIL FUEL DISPLACEMENT	0.102

HYDRO EMISSION AS MULTIPLE OF THERMAL[b] = 3.6

[a] Pre-dam ecosystem fluxes: CH_4 sink in forest soil, N_2O source in forest soil, and CH_4 source from forest termites.

[b] Net emission exclusive of fossil fuel displacement/Displaced fossil fuels

Fig. 1

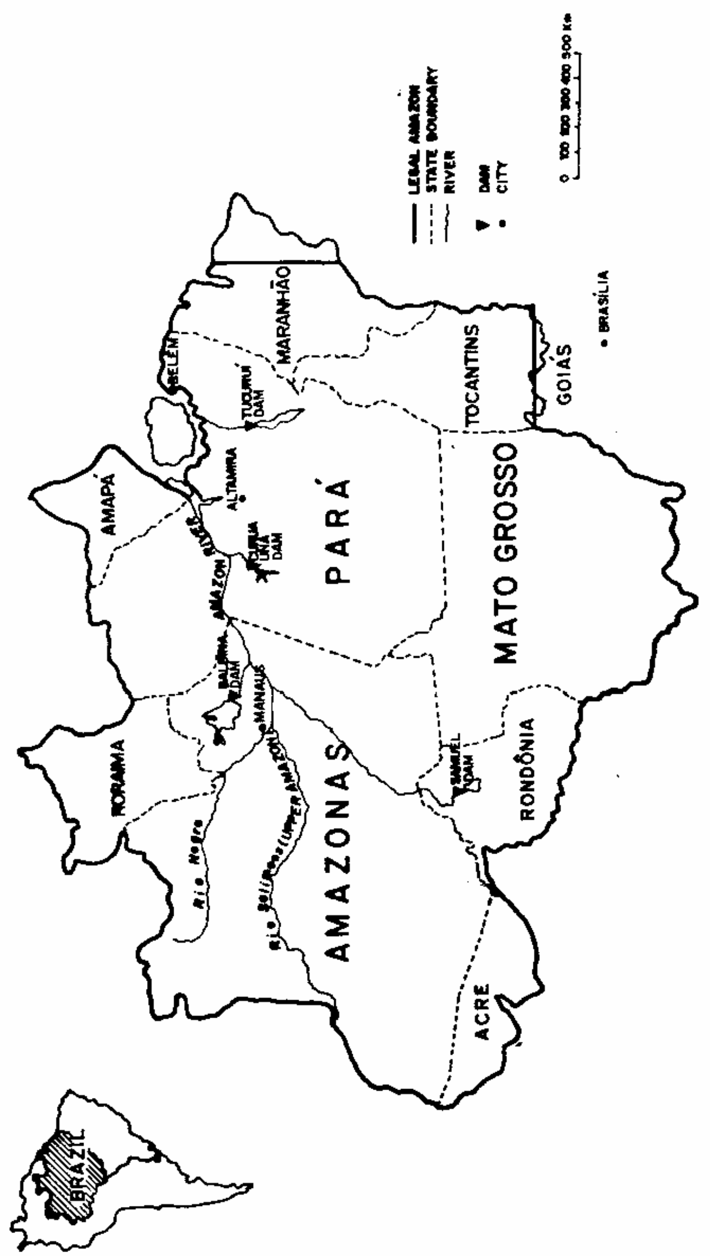
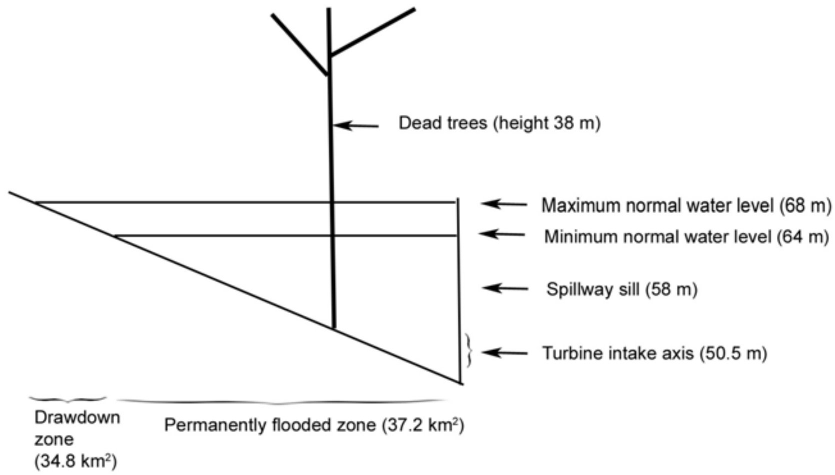

LEGAL AMAZON
STATE BOUNDARY
RIVER
DAM
CITY
0 100 200 300 400 500 Km
BRASÍLIA
AMAPÁ
BELÉM
MARANHÃO
TUCURUÍ DAM
ALTAMIRA
AMAZON RIVER
PARÁ
TOCANTINS
GOIÁS
MATO GROSSO
RORAIMA
BALBINA DAM
MANAUS
Rio Negro
AMAZONAS
SAMUEL DAM
RONDÔNIA
ACRE
BRAZIL

Fig. 2


Dead trees (height 38 m)
Maximum normal water level (68 m)
Minimum normal water level (64 m)
Spillway sill (58 m)
Turbine intake axis (50.5 m)
Drawdown zone (34.8 km²)
Permanently flooded zone (37.2 km²)