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GREENHOUSE GAS EMISSIONS FROM A HYDROELECTRIC RESERVOIR (BRAZIL'S TUCURUÍ DAM) AND THE ENERGY POLICY IMPLICATIONS

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ABSTRACT

Greenhouse gas emissions from hydroelectric dams are often portrayed as nonexistent by the hydropower industry, and have been largely ignored in global calculations of emissions from land-use change. Brazil's Tucuruí Dam provides an example with important lessons for policy debates on Amazonian development and on how to assess the global warming impact of different energy options. Tucuruí is better from the point of view of power density, and hence greenhouse gas emissions per unit of electricity, than both the average for existing dams in Amazonia and the planned dams that, if all built, would flood 3% of Brazil's Amazon forest. Tucuruí's emission of greenhouse gases in 1990 is equivalent to 7.0-10.1 × 10^6 tons of CO_2-equivalent carbon, an amount substantially greater than the fossil fuel emission of Brazil's biggest city, São Paulo. Emissions need to be properly weighed in decisions on dam construction. Although many proposed dams in Amazonia are expected to have positive balances as compared to fossil fuels, substantial emissions indicated by the present study reduce the benefits often attributed to the planned dams.

1. Introduction

Hydropower is often promoted by government authorities as a "clean" source of energy, in contrast to fossil fuels (e.g., de Souza, 1996). While fossil fuel contributions to global warming are well known, hydroelectric dams are not free of impact. Hydroelectric dams in tropical forest areas emit greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4). The ratio of impact to benefit varies tremendously among dams depending on their power output. Tucuruí, the dam examined in this paper, has a more favorable balance than either the average existing dam or the average planned dam in Brazilian Amazonia.

Tucuruí serves as a testing site for the country's plans for hydroelectric development in Amazonia. The possibility of claiming carbon credit for planned hydroelectric dams often arises in discussions in Brazil on the Kyoto Protocol's Clean Development Mechanism. Greenhouse gas emissions clearly cannot be ignored in such discussions. Even more important are the social and environmental impacts caused by many dams, which have caused these projects to be questioned as a forms of

"clean development" (Fearnside, 1999a). The Tucuruí Dam provides an excellent example of these problems (Fearnside, 1999b, 2001).

This paper estimates greenhouse gas emissions for Tucuruí for 1990, the base year for national inventories of greenhouse gas emissions under the United Nations Framework Convention on Climate Change (UN-FCCC). The estimate includes emissions from various sources of emission that have been ignored in previous estimates for Amazonian reservoirs, such as methane release from water passing through the spillway and turbines.

2. The Tucuruí Reservoir

Brazil's Tucuruí Dam was completed in 1984 on the Tocantins River, a north-flowing tributary to the Amazon River located in Pará (Figure 1). The reservoir's area is officially 2430 km^2 at the normal operating level of 72 m above mean sea level (msl). LANDSAT satellite measurements estimated the area at 2247 km^2 in 1989 (INPE, see Fearnside, 1995, p. 13) and 2800 km^2 in June and July 1996 (de Lima et al., 2000). The current dam (Tucuruí-I) has 3960 MW of installed capacity. A second phase (Tucuruí-II) is expected to double the installed capacity to 8085 MW by 2002 (Brazil, Programa Avança Brasil, 1999).

[Figure 1 here]

The Tucuruí Dam is one of 10 focal studies of the World Commission on Dams, particularly for understanding greenhouse gas emissions from hydroelectric development (WCD, 1999). Tucuruí has the largest reservoir in Brazilian Amazonia after Balbina (which is often dismissed by electrical authorities as atypical because its low power density). Balbina has especially high emissions due to its large reservoir relative to the generating capacity that could be installed at a location with flat topography and low streamflow (Fearnside, 1995, 1996a; Rosa et al., 1996a). Tucuruí-I (the present configuration of Tucuruí) has 1.63 watts (W) of installed capacity per m^2 of reservoir surface, whereas Brazil's national power authority (ELETROBRÁS) has calculated the average power density for the entire hydroelectric potential of the Amazon Region to be only 1 W/m^2 (Rosa et al., 1996b, p. 6). This refers to the full list of dams planned in Brazil's 2010 Plan, regardless of the intended date of construction (Brazil, ELETROBRÁS, 1987; see Fearnside, 1995). The equivalent figure for the 5537 km^2 of water surface in the four existing large dams (whose total installed capacity

is 4490 MW) is 0.81 W/m^2, or only half the power density of Tucuruí-I.

3. Reservoir Emissions

3.1. Emissions from Above-Water Decay

When tropical forests are flooded by reservoirs, the trees are left standing in the water with the exception of small areas cleared near the dams. A substantial part of the biomass is left projecting above the water surface and decays aerobically. This source of emission has been ignored in most discussions of the global warming impact of hydroelectric development. Parameters for above-water emissions calculations for the Tucuruí reservoir are given in Table I.

[Table I here]

3.2. Emissions from the Reservoir Surface

Several recent studies in reservoirs indicate that methane emissions show a large peak in the first years after filling, followed by a decline. At age one year, the Petit-Saut reservoir in French Guiana released 1300 mg CH_4/m^2/day from the water surface (530 from bubbling and 770 from diffusion) (Galy-Lacaux et al., 1997). The Curuá-Una reservoir, at age 21 years, released 66 mg CH_4/m^2/day (16 from diffusion and 50 from bubbling) (Duchemin et al., 2000). Gatun Lake in Panama at age 84 years released 412 mg CH_4/m^2/day (12 from diffusion and 400 from bubbling) (Keller and Stallard, 1994). Measurements of methane emissions specific to Tucuruí indicate wide spatial and temporal variations (Table II).

[Table II here]

Considerable controversy has surrounded the methodology for estimating emissions from the reservoir surface. An inverted funnel sampling device used by the University of São Paulo at São Carlos measures bubbling emissions only (e.g., Rosa et al., 1996b, c, 1997a). Diffusion chambers used by INPE (de Lima and Novo, 1999; de Lima et al., 2000) and by studies by the University of Quebec at Montreal at other Amazonian reservoirs (Duchemin et al., 2000) captured both bubbles and diffusion emissions. However, these chambers are less efficient than funnels for estimating the bubbling component because chambers make collections using a series of brief (typically 15-minute) emplacements that can easily miss the sporadic bursts of bubbling activity (Keller and

Stallard, 1994). Recent work at Tucuruí (age 14-15 years) by the University of São Paulo at São Carlos with both funnels and diffusion chambers indicates that bubbling only contributes 6-16% of total surface emissions of 14.6-205.3 mg $CH_4/m^2/day$ (Matvienko et al., 2000). At the Curuá-Una reservoir (age 21 years), Duchemin et al. (nd) measured both bubbling and diffusion and found bubbling accounts for 32-81% of total surface emissions of 37.5-80.2 mg $CH_4/m^2/day$. At Petit-Saut (age 1 year), Galy-Lacaux et al. (1997) found a bubbling contribution of 59% to a total surface emission of 1300 mg $CH_4/m^2/day$. In coves at Gatun Lake (age 84 years), bubbling contributed 97% of the 400 mg $CH_4/m^2/day$ average surface emission (Keller and Stallard, 1994). Given the lack of any consistent proportionality between bubbling and diffusion, only estimates that include both bubbling and diffusion were used in the present study (Table II).

The area covered by macrophytes (mostly floating weeds such as water hyacinth, Eichhornia crassipes) is an essential determinant of methane flux. At the high-water period (14 August 1988), Novo and Tundisi (1994, p. 149) found that 21% of the Tucuruí reservoir was covered with macrophytes based on LANDSAT imagery. Based on the data and assumptions of Novo and Tundisi (1994), for the high water-level period, and on the assumptions of these authors for the remainder of the year, the average area occupied by macrophytes over the annual cycle was 286.4 km^2, or 13.1% of the 2188 km^2 average area of the reservoir that can be computed for the same year. At Tucuruí, macrophytes exploded in the first year after filling and then died back to lower levels as the nutrient content of the water declined. In 1986 (two years after closing) the area of macrophytes was estimated at 620 km^2 (Brazil, ELETRONORTE, 1988a, p. 94), or about 26% of the reservoir area when full. A study by de Lima et al. (2000) shows June-August (high water level) macrophyte cover decreasing from 39% in 1986 to 11% in 1994, which appears to be a stable level. The cover would have been 21% in 1988, corresponding to the scenario in Table III. Initial explosive growth followed by decline has also been the pattern for macrophytes at other tropical reservoirs such as Brokopondo in Surinam (Leentvaar, 1966), Guri in Venezuela (Vilarrubia and Cova, 1993) and Balbina (Fearnside, 1989; Walker et al., 1999), Curuá-Una (Junk et al., 1981) and Samuel (Bohdan Matvienko, public statement, 24 February 2000) in Brazil.

[Table III here]

In seven studies in <u>várzea</u> (floodplain) lakes, areas with macrophytes had 3.25 times more CH_4 emissions than open water (see Fearnside, 1995, p. 15). At Tucuruí in September 1992, an area with macrophytes had 1056 times more CH_4 emission by bubbling than open water in the river channel, 0.8 times as much as open water with standing trees, and 5.8 times as much as open water in a cove without standing trees (Rosa et al., 1996c, p. 150). The greater areas of macrophytes in a reservoir's early years contribute to a greater pulse of methane emissions during these years.

A large area of the reservoir bottom is seasonally exposed. Considering the 58 m above msl minimum operating level for Tucuruí-I (Brazil, ELETRONORTE, 1989, p. 64), this area occupies 858 km^2 (Fearnside, 1995, p. 13), while considering the drawdown to 68 m above msl in August 1988 (before all turbines were operational), the area occupied 397 km^2 (Novo and Tundisi, 1994). When flooded, the drawdown area offers ideal conditions for generation of methane, as well as for methylation of mercury in the soil. In the Samuel reservoir, for example, areas like this released 15.3 g C/m^2/year as CH_4 through bubbling when seasonally flooded, as compared to 7.2 g C/m^2/year among standing dead trees in permanently flooded areas and only 0.00027 g C/m^2/year in the main channel (Rosa et al., 1996c, p. 150).

Based on information on habitat areas and emission rates (Tables II and III), one can calculate approximate emissions through bubbling and diffusion of CH_4 from Tucuruí (Table IV). This assumes that the area covered by macrophytes throughout the annual cycle follows the assumptions of Novo and Tundisi (1994, p. 150), which are that the maximum macrophyte area (505.4 km^2) applies to four months (assumed to be May-August), while for two months (assumed to be March and April) the area is 50% of the maximum and is replaced by open water (25%) and exposed drawdown (25%), and for six months (assumed to be September-February) the macrophyte area is 30% of the maximum and is replaced by open water (15%) and exposed drawdown (15%). The year is divided into two seasons on the basis of streamflow: a low-flow period (January-May) and a high-flow period (June-December). The year could also be divided on the basis of water level (low = September-February, high = March-August) or rainfall (dry = July-November, wet = December-June).

[Table IV here]

3.3. Emissions from the Turbines

In 1991 Tucuruí produced 18.03 TWh of electricity (Brazil, ELETRONORTE, 1992, p. 3), or 2058 MW. The dam's annual production was expected to be 2476 MW by 1991 (Brazil, ELETRONORTE, 1989, p. 58), or 20.3% more than was actually produced; had production been higher, CH_4 emissions from water passing through the turbines would also have been proportionately higher. Each turbine has a nominal capacity of 350 MW and a power factor of 95% (i.e., 332.5 MW of effective production), and uses 575 m^3/s of water (Brazil, ELETRONORTE, 1989, p. 17). Each turbine therefore uses 18.1×10^9 m^3/year of water, and 18.3 MW is generated per 10^9 m^3 of water. A total of 112.2×10^9 m^3 of water passed through the turbines in 1991. The methane concentration at 30-m depth was 6 mg CH_4/liter in March 1989 (unpublished data of J.G. Tundisi cited by Rosa et al., 1997a, p. 43). Work at the Petit-Saut Dam by Galy-Lacaux et al. (1999, p. 508) shows that CH_4 concentrations fluctuate on a seasonal basis in a pattern that corresponds to the balance between water inflow and outflow in the reservoir. The amplitude of the oscillation is such that the maximum concentration is at least 50% higher than the minimum in each annual cycle. The one available profile for CH_4 concentrations in the water at Tucuruí is from March 1989, which is during the high water-flow period when the time series at Petit-Saut (Galy-Lacaux et al., 1999) indicates that CH_4 concentrations are at a minimum. If the relative magnitude of the seasonal oscillation in CH_4 concentration at Petit-Saut applies to Tucuruí, the concentration at 30-m depth should vary (at least) between 6 and 9 mg CH_4/liter, with a mean value of 7.5 mg CH_4/liter (Figure 2).

[Figure 2 here]

This can be regarded as a conservative estimate of the concentration in the water passing through the turbines, since CH_4 concentration increases with depth and the intake is at a depth of 35.4 m when the reservoir is at the operating level of 72 m above msl (Brazil, ELETRONORTE, 1989, p. 157). Based on an annual average methane concentration of 7.5 mg CH_4/liter at the level of the turbines, one can calculate that the amount of CH_4 exported from the reservoir through the turbines in 1991 would have been 0.842×10^6 t. However, the seasonal oscillation acts to reduce the amount of CH_4 exported below this value because power generation is greatest during the high-flow period, when the concentration of CH_4 in the water is least. An adjustment for this effect is calculated in Table V, reducing the 1991 export of CH_4 by 6.7% to 0.785×10^6 t.

[Table V here]

The fate of the CH_4 in water passing through the turbines can be estimated based on data from the Petit-Saut Dam (Galy-Lacaux et al., 1997). Totaling three measurements at Petit-Saut, an average of 87.1% of the methane was degassed immediately when the water emerged from the turbines; of the remaining methane, 18.4% was degassed from the river water and 81.6% was oxidized to CO_2 in the first 40 km downstream of the dam. Based on these data, the 1991 release from water passing through the turbines at Tucuruí totaled 0.702×10^6 t CH_4 (0.684×10^6 t at the turbines and 0.019×10^6 t in the river).

A significant difference between Tucuruí and Petit-Saut is an aerating device built about 100 m downstream of the Petit-Saut Dam. When dam operation began in June 1994, almost all of the fish died in the river below the dam, motivating suspension of generation while the device, a 4-m-high dual-nappe weir, was built to create an artificial waterfall and provide more oxygenated water to the river below. The weir was completed in February 1995 (Gosse, 1999). An unintended byproduct of this is the release of additional methane, some of which would otherwise have been oxidized to CO_2 by bacterial activity in the river or in the ocean (40 km downstream). In the case of Tucuruí, however, one can assume that most of the CH_4 in the water is also released when water passes through the turbines because of the sudden drop in pressure. For example, at Balbina, water samples from the reservoir bottom (29 m maximum depth) foam with CH_4 and CO_2 bubbles when brought to the surface (Bohdan Matvienko, public statement, 24 February 2000).

The Petit-Saut data do not allow separation of the amount degassed immediately as the water emerges from the turbines from that degassed at the artificial waterfall. Galy-Lacaux et al. (1997, p. 479) calculate the combined release at these two points from the concentrations of CH_4 in the water column just above the dam and in the water below the artificial waterfall. Of the three such paired measurements reported by Galy-Lacaux et al. (1997, p. 497), the average CH_4 concentration drops from 8.11 mg/liter to 0.77 mg/liter, or 90.5%. The average amount degassed at the turbines and waterfall totaled 98.2 t CH_4/day (89.9% of the CH_4 exported through the turbines, or 97.7% of the 100.5 t CH_4/day total emissions from turbined water). All release in the river occurs in the first 20-30 km below the weir; the average of the three measurements of this release was 2.3 t CH_4/day, which

represents 2.1% of the CH_4 exported through the turbines, or 2.3% of the total emissions from turbined water. If the artificial waterfall did not exist, the amount degassed in the river would probably be higher than the 11.0 t/day measured in the Petit-Saut case (21.0% of the CH_4 entering the river below the weir) because of the higher concentration of CH_4 that would enter the river at this point. This makes it possible to calculate lower and upper bounds for the emission from water passing through the turbines at Tucuruí. Considering the percentages released as 21.0%-89.9% based on the Petit-Saut results, the release from the turbines at Tucuruí in 1990 was $0.165\text{-}0.702 \times 10^6$ t CH_4. The total methane released from water passing through the turbines at Tucuruí was 2-8 times the total release from bubbling and diffusion in the reservoir itself.

3.4. Emissions from the Spillway

An additional major source of CH_4 emissions at Tucuruí is water released through the spillway. This water is not taken from the surface, but rather comes from a level 52 m above msl (Brazil, ELETRONORTE, 1989, p. 146). Water released from the spillway comes from a depth of 20 m when the reservoir is at the normal operating level of 72 m above msl. Water shoots out from under a series of 23 steel doors when they are raised; normally this is a thin sheet from the bottom of the spillway bay, although these gigantic doors (each 21-m high and weighing 220 t) can be pivoted upward to allow major floods to pass. With the exception of such flood events, the offtake is therefore the 52 m above msl elevation of the spillway crest. In each spillway, the water descends a chute to 30 m above msl, where it is thrown into the air by a ski jump-like device and plunges an additional 28 m to a concrete-lined dissipation basin below. The great white plume of spray formed when all 23 of the 20-m wide spillways are open is undoubtedly the most spectacular and frequently photographed sight at the dam. The completeness and instantaneous nature of the aeration make it a safe assumption that all CH_4 dissolved in the water is released immediately to the atmosphere.

Emissions from the spillway would be very large if the reservoir were always kept at its full water level. Considering the long-term average streamflow of 11,107 m^3/s (Brazil, ELETRONORTE, 1989, p. 17), or 350.5×10^9 m^3/year, and the seasonally adjusted CH_4 concentration of 3.75 mg CH_4/liter at 20-m depth, the spillway would have emitted 0.893×10^6 t CH_4 in 1990, equivalent to 5.1×10^6 t of CO_2-equivalent C. However, several factors reduce the annual

emission from water released through the spillway. One is the seasonal cycle in CH_4 concentration, the greatest release from the spillway being during the high-flow period when the CH_4 concentration is lowest. Another factor is the effect of drawdowns: as the water level falls, the depth of the spillway intake relative to the water surface decreases, presumably with a corresponding reduction in CH_4 concentration at the spillway level. These two effects reduce the estimated export of CH_4 through the spillway to 0.535×10^6 t (Table VI), a decrease of 40.1%. An effect not corrected for is the thickness of the sheet of water allowed to pass through the spillway: although normally only a narrow slit is opened, during larger floods the floodgates can be raised higher, allowing water nearer the surface (with lower CH_4 content) to escape.

[Table VI here]

3.5. Loss of Sources and Sinks in Living Forest

When standing tropical forest is flooded and killed, the forest's natural sources and sinks of greenhouse gases are lost. These include the loss of an annual uptake of carbon by the standing forest. Studies using eddy-correlation techniques indicate that intact Amazonian forests have a net uptake carbon at present (e.g., Grace et al., 1995; Mahli et al., 1998). Although this effect cannot be permanent (over the long-term the forest C stocks cannot continue to grow), the uptake effect nevertheless constitutes an addition to the impact of killing large areas of forest by flooding. Other losses include loss of a small methane sink in tropical forest soil and loss of a very small methane source from forest termites. On the other hand, a source of nitrous oxide (N_2O) emissions is eliminated by the flooding. Amazonian forest soils at Paragominas (where the seasonal distribution of precipitation is similar to that at Tucuruí) emit an estimated 8.68 kg of N_2O/ha/year (Verchot et al., 1999, p. 37), equivalent to 0.73 t CO_2-equivalent C/ha/year considering the 100-year global warming potential of 310 adopted by the Kyoto Protocol for N_2O. The 1926 km^2 of forest flooded at Tucuruí (Fearnside, 1995, p. 11) therefore emitted 0.117×10^6 t of CO_2-equivalent C annually as N_2O prior to flooding. The area flooded by Tucuruí, as with most hydroelectric dams, was not a wetland prior to flooding, but rather was an area of rapids on the river that had topography sloping steeply enough to maintain well-drained soils. The pre-reservoir emission was therefore not the much larger source of either CH_4 or N_2O that has sometimes been implied. The net

effect of losses of sources and sinks in living forest is calculated in Table VII.

[Table VII here]

3.6. Global Warming Impact of 1990 Emissions

In summary, the major sources of methane emissions at Tucuruí in 1990 were as follows, in 10^6 t CH_4: 0.0937 from bubbling and diffusion, 0.1649-0.7025 from the turbines, and 0.5353 from the spillway (Table VIII). Small additional contributions were made by termites in above-water decay and from loss of the sink in forest soil, and a small reduction in the flux resulted from loss of forest termites. The CH_4 emission totaled 0.79-1.33 × 10^6 t of gas; considering a global warming potential of 21 (Schimel et al., 1996, p. 121), this is equivalent to 4.5-7.6 × 10^6 t of CO_2-equivalent C. Emissions of CO_2 in 1990 were estimated at 9.68 × 10^6 t of CO_2 gas, or 2.64 × 10^6 t of C. Adjustment for loss of the N_2O source in forest soil decreases the emission by 1-2%. The contribution of methane represented 64-75% of the total greenhouse gas impact of 7.0-10.1 × 10^6 t of CO_2-equivalent C in 1990 (Table VIII). As explained in Table VIII (note a), 1990 emissions are calculated from parameters from the various years for which information is available.

[Table VIII here]

4. Discussion

4.1. Uncertainty

The reliability of the present estimate is most sensitive to the value of two parameters: the concentrations of CH_4 in the water passing through the spillway and through the turbines. Here a set of values is used that was measured at Tucuruí in March 1989 by José G. Tundisi (cited by Rosa et al., 1997a, p. 43). These values are adjusted for seasonal oscillations based on the series of measurements at Petit-Saut (Galy-Lacaux et al., 1999). The existence of seasonal oscillations indicates the importance of a series of measurements to capture this source of variation. Most research effort aimed at quantifying greenhouse gas emissions from hydroelectric dams, including Tucuruí, has been devoted to measurements of fluxes at the reservoir surface. However, the calculations in the present paper show clearly that the greatest gains in reducing uncertainty in the overall estimate would come from better information on the CH_4

concentrations in water entering the turbines and the spillway, and the fate of CH_4 in the river below the dam.

Methane fluxes from the reservoir's surface, particularly through bubbling, are also subject to cycles. On a seasonal basis, emissions per unit area are higher at any given location in the reservoir when the water level is low. The frequent drawdowns in reservoir management can be expected to result in greater CH_4 release through bubbling. The large releases that occur when water levels fall are likely not to be detected by the brief measurement "campaigns" that are the basis of currently available data.

Bubbling emissions are greater in shallower water because it has less vertical distance over which CH_4 bubbles released from the sediments can be oxidized before reaching the surface. Also, hydrostatic pressure on the sediments is less, leading to greater release of bubbles from this supersaturated environment. In addition, methanogenesis rates are sensitive to temperature, and the cooler sediments at greater depths would produce less CH_4 than sediments in shallow areas. At Gatun Lake, for example, over a depth gradient from 0.5 to 10 m, bubbling rate decreased by a factor of 10, of which a factor of 2.3-3.9 could be explained by temperature and pressure differences (Keller and Stallard, 1994, p. 8315). The substantial additional effect of depth may be due to greater inputs of terrestrial C in the shallow near-shore areas (Keller and Stallard, 1994). In addition to the effect of depth on emission variations over time, this factor also shows the great spatial variation that exists over the reservoir surface and the care needed to obtain representative samples and interpret these through appropriate weighting by the area of each habitat and depth category. The three-zone division used in the current paper is the maximum level of detail that current data permit, but as more measurements become available, a finer breakdown of depth and habitat classes could improve the reliability of the estimates.

On a diurnal basis, emissions are higher during the day than at night due to greater wind and wave action (Duchemin et al., 2000; Keller and Stallard, 1994). Greater bubbling fluxes in the afternoon at Tucuruí may also be due to a diurnal cycle in atmospheric pressure that is equivalent to an 18-cm water level fluctuation in terms of hydrostatic pressure exerted at the bottom (de Lima and Novo, 1999). Since many reported measurements do not specify that a 24-hour monitoring cycle was included, this is a source of additional uncertainty.

The Galy-Lacaux et al. (1999) study at Petit-Saut indicates that CH_4 concentrations decline over time, falling from 14 to 10 mg/liter in the first four years of impoundment (the measurement period at Petit-Saut), and expected to decline to 0.3 mg/liter at age 20 years based on present CH_4 levels at a comparable dam in the Ivory Coast. The projected concentration at Petit-Saut six years after impoundment (the reservoir age for the current estimate for Tucuruí) is 4 mg/liter. However, Galy-Lacaux et al. (1999) used an average CH_4 concentration over the full vertical profile of the water column at a sampling station near the dam as the estimate of the concentration in the water passing through the turbines. Petit-Saut differs from Tucuruí in some significant ways affecting the choice of a CH_4 value. The reservoir at Tucuruí is approximately twice as deep at the dam as Petit-Saut, with the midpoint of the intakes for the turbines located at a depth of 35.4 m (below the 34-m total depth of the reservoir at Petit-Saut). In addition, Petit-Saut has a special structure built to minimize the discharge of anoxic water (which is also the most methane rich). This is an underwater dike built parallel to the dam 60 m upstream as a measure to immobilize the lower half of the water column and draw only relatively well-oxygenated surface water into the turbine intakes (Sissakian and Desmoulins, 1991). Tucuruí has no such structure, making a CH_4 concentration value measured as close as possible to the level of the turbine intakes a more appropriate choice than the mean for the water column.

The present estimate of emissions from Tucuruí is conservative for several reasons. The estimate ignores "unusual" events, such as storms, that result in much higher than average emissions from the reservoir surface. These events have been found to represent a substantial portion of the annual emissions in reservoirs in northern Canada (Duchemin et al., 1995). Storms can cause large inputs of organic matter from the watershed, such as leaves, twigs and other debris; they can also create seiches that bring the oxycline to the surface, allowing release from methane-saturated deep water (Donald D. Adams, public statement, 24 February 2000).

The use of data from different years to produce an approximate estimate for 1990 adds to the uncertainty. Some of the effects result in overestimation of the 1990 emission, such as using macrophyte areas from 1988 and CH_4 content of the water from 1989, turbine and spillway depths from 1988, and turbine water flow from 1991. Other factors underestimate 1990 emission, such as bubbling and

diffusion per unit of area from 1996-1997 and spillway flow from 1991.

The present estimate does not include emissions from deforestation by the displaced population. The substantial emissions from dam construction that would be needed for a full-chain energy analysis ("life-cycle analysis") are also not included. Future impacts would also include emissions from upstream dams planned to regulate the flow of the Tocantins River.

4.2. Comparison with Previous Estimates

Greenhouse gas emissions from the Tucuruí reservoir for a single year (1990) have been estimated (Fearnside, 1995), and the analysis was subsequently extended from a single year to compute the amount and timing of emissions over a 100-year time period, which could then be compared to the emissions that would be produced by generating the same amount of energy from fossil fuels (Fearnside, 1997a). Factors considered included the initial stock and distribution of carbon, decay rates and pathways (leading to CO_2 and CH_4), and losses of power in transmission lines. Factors not considered included forest degradation on islands and reservoir shores, nitrous oxide sources in drawdown zones and transmission lines, additional methane emission pathways for release from standing trees, water passing through the turbines, etc. Construction-phase emissions were also not included, nor were emissions from deforestation by people displaced by (and attracted to) the project.

Earlier calculations assumed that only 10% of the water surface was covered by macrophytes (Fearnside, 1997a). The average area used in the current calculation was 13.1% (Table III). However, the emission from macrophyte beds is much lower under the current calculation (72 mg CH_4/m^2/day at high water and 68 mg CH_4/m^2/day at low water) than the 174.7 mg CH_4/m^2/day used in previous calculations (Fearnside, 1995, 1997a). This probably indicates that the present calculation is conservative, since the previous ones, although based on data from <u>várzea</u> lakes rather than from Tucuruí, were based on many more observations (e.g., Bartlett et al., 1990; Devol et al., 1990; Wassmann and Thein, 1989).

Most of the global warming impact in the earlier calculations (Fearnside, 1995) came from CO_2 released by above-water decomposition of wood: in 1990 CO_2 contributed 83% and CH_4 17%, considering the global warming potential of 21 for CH_4 for the impact of a ton of this gas relative

to a ton of CO_2 currently used by the Intergovernmental Panel on Climate Change (IPCC) (Schimel et al., 1996, p. 121). In the above analysis, methane emissions were assumed to be relatively constant over the time horizon, rather than having an initial peak followed by a decline to a lower plateau.

Inclusion of CH_4 emissions from water released through the turbines and the spillway, which were not included in previous estimates, substantially increases the reliability of the present calculation. These sources increase total emission of CH_4 as compared to earlier emissions estimates (Fearnside, 1995, 1997a), which included CH_4 from decomposition of submerged forest, for which assumptions had been used that now appear to be conservative. The CH_4 production estimates based on assumptions about decomposition rates and pathways have been replaced with more reliable estimates based on measurements of CH_4 concentration in the water and release through the turbines and spillway. This significantly changes previous estimates for 1990 (Fearnside, 1995), in which CO_2 contributed 83% and CH_4 17%. The revised estimate indicates lower methane emissions from the reservoir surface (mainly due to lower values for emission from macrophytes per m^2).

The results of the present study are compared with those of previous studies in Table IX. Studies vary widely, not only in their final results but also in the completeness of their coverage of emissions sources. Estimates producing very low final results ignore CH_4 emissions from water passing through the turbines and spillway and CO_2 emissions from decay of above-water biomass. Mainly due to the inclusion of emissions from the turbines and spillway, calculations in the present study more than doubles this author's previous estimate for emissions in 1990 (Fearnside, 1995) from 3.1×10^6 t CO_2-equivalent C (considering the current global warming potential of 21 for CH_4) to 8.6×10^6 t CO_2-equivalent C, this being the midpoint of the $7.0\text{-}10.1 \times 10^6$ t CO_2-equivalent C range that results from uncertainty concerning the percentage of CH_4 released in turbined water. Despite high and poorly quantified uncertainty, the finding of substantial emission is believed to be quite robust. The results of this study indicate emissions one to two orders of magnitude greater than the reservoir-surface emission studies that currently form the basis of Brazilian policy on global warming and hydroelectric dams (Table IX).

[Table IX here]

4.3. Time Path of Emissions

A key question for the future will be whether the concentration of CH_4 in the water will decline to a plateau at a very low level, such as the 0.32 mg/liter found by Galy-Lacaux et al. (1999) at a 20-year-old African reservoir. One factor determining this will be the relative importance of different sources of the carbon that decays to methane. The rapid decay of soft plant parts from the original forest is probably complete in all of these reservoirs by age six years, but continued inputs come from the watershed in the form of dissolved organic carbon and organic debris brought by inflowing water. It is also generated within the reservoir by primary production, especially by macrophytes, using nutrients supplied to the reservoir from the inflow. In a reservoir like Tucuruí, with large-scale deforestation and consequent soil erosion in the watershed upstream of the dam, these inputs of nutrients and of organic carbon can be expected to continue over the long term at high levels. The coverage of macrophytes declined in the reservoir over the 1986-1994 period, but appears to have stabilized at the level of coverage observed in 1994, when these plants covered 11% of the water surface during the high-water period (de Lima et al., 2000).

Emissions from Tucuruí today would differ from those in 1990. An important factor increasing emissions is that the 1991 power generation data used in the estimate for 1990 was for a period before all of the turbines had been installed in the Tucuruí-I phase of the dam. On the other hand, above-water biomass decay would have slowed over the years as this carbon stock disappears, and the coverage of macrophytes declined from 21% to the plateau level of 11% of the high-water period surface area.

Greater fluctuation in the water level (with more turbines installed) also leads to greater emissions. When the water level in the reservoir falls, vegetation quickly regrows on the exposed land. This soft green biomass rapidly decomposes when the water level subsequently rises and floods the drawdown area, releasing methane under the anoxic conditions that prevail on the bottom. Because these areas are relatively shallow, a substantial portion of the bubbles that form can reach the surface before the methane can be oxidized in the water column. Green vegetation in flooded drawdown zones was found to be a significant source of methane bubbling at Balbina (Bohdan Matvienko, public statement, 24 February 2000).

4.4. Time Preference and Energy Choices

Brazil as a whole emitted 53 × 10^6 t of carbon annually from fossil fuels in 1990 (La Rovere, 1996). The 7.0-10.1 × 10^6 t emission of CO_2-equivalent C from Tucuruí in 1990 therefore represents 13-19% of the fossil fuel emission from the entire 170 million Brazilian population. The Tucuruí emission is 1.3-1.9 times that of the fossil fuel burned by the 17 million population of Brazil's largest city, São Paulo (10% of Brazil's population).

The above-water wood that produced 25-36% of the emission from Tucuruí in 1990 will eventually disappear. The methane emission that makes up the remainder of the dam's global-warming impact will decline to a lower plateau, but a poorly quantified part of this will continue as a permanent source. A São Paulo-sized emission source may therefore be permanent. These impacts consider the 100-year global warming potentials without discounting (currently used by the Kyoto Protocol); were discounting or other time-preference weighting mechanisms to be applied, the relative impact of hydroelectric dams could be higher than those calculated here by a factor of two or more (Fearnside, 1997a).

Hydroelectric power generation produces large pulses of CO_2 and CH_4 emissions in the first years after filling the reservoir, while thermal generation produces a constant flux of gases in proportion to the power generated. The analysis of the timing of emissions (Fearnside, 1997a) indicates that the average CO_2 molecule in the atmospheric load contributed by Tucuruí enters the atmosphere 15 years earlier than the average molecule in the comparable load from fossil fuel generation. This means that, considering a 100-year time horizon, a ton of CO_2 emitted by Tucuruí has more global warming impact than a ton emitted by fossil fuel, whether or not discounting is applied to greenhouse gases. If discounting is applied, then the relative impact of the hydroelectric option is increased.

Decisions on the time scale over which dams and their global warming impacts are assessed, and on the weighting for time (as by discounting) over the course of the time horizon, will have dramatic influence on the choices that are made on energy development options. They will also influence the assessment of the worldwide contribution to global warming made by reservoirs. Decisions on time horizons and discount rates should be made to best represent the interests of society. If long time horizons are applied without discounting (or other

forms of time-preference adjustment) within the time horizon, the result would be to give little value to delaying global warming. Although no agreement on these issues has yet been reached, this author has advocated using a time horizon of 100 years in conjunction with discounting at an annual rate of about 1%, or its equivalent under an alternative time-preference weighting system (Fearnside, 2000a, b; Fearnside et al., 2000).

When global warming is delayed, the impacts (including human life and other non-monetary impacts) that would have occurred over the course of the delay represent benefits to society. Translating this societal value into the decision-making tools represented by time horizon and discounting will result in giving greater weight to short-term impacts such as the peak of emissions from dam construction and the first few years of impoundment and the short-lived gases such as methane produced by reservoirs. Choice of a 100-year time horizon would be consistent with many dam life-cycle analyses and with the global warming potentials currently adopted in an addendum to the Kyoto Protocol (Decision 2/CP.3) for the Protocol's first commitment period (2008-2012). A decision for the first commitment period is expected to be made at the Sixth Conference of the Parties in November 2000. Regardless of what decision is made, the increasingly unavoidable human impacts and the very long-lasting nature of global warming mean that international negotiations will continue for many years beyond the first commitment period. This author believes that this process will tend towards increasing weight being placed on time, and consequently to an increase in the impact attributed to emissions from hydroelectric dams relative to those from many other energy alternatives.

5. Conclusions

Hydroelectric dams in tropical forest areas produce substantial emissions of greenhouse gases. Although uncertainty regarding the amount of emission is still high, the magnitude of emissions involved is sufficient to both affect global levels of greenhouse gases and to demonstrate the need for careful comparisons of hydroelectric and other energy options as a part of the decision-making process. Tucuruí, with a global warming impact in 1990 greater than that of the fossil fuel burned by the city of São Paulo, provides a reminder of the potential scale of emissions from the dozens of reservoirs that are planned for construction in Amazonia over the coming decades.

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FIGURE LEGENDS

Fig. 1 – Locations mentioned in the text.

Fig. 2 – Methane concentration profile in Tucuruí. Observed March 1989; data are from measurements by J.G. Tundisi, cited by Rosa et al. (1997a, p. 43). Adjusted annual mean values are calculated as described in the text, based on proportional seasonal variations at Petit-Saut (Galy-Lacaux et al., 1997, 1999).

TABLE I

Parameters for Tucuruí reservoir emission from above-water biomass

Parameter	Value	Units	Source
Above-ground fraction	0.759		Fearnside (1997b, p. 37)(*)
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^{-1}	Assumption; note seasonal drying accelerates rate (Polunin 1984, p. 129).
Above-water decay rate (0-4 yr)	-0.1680	fraction yr^{-1}	Assumed same as felled forest (Fearnside 1996b, p. 611)(*)
Above-water decay rate (5-7 yr)	-0.1841	fraction yr^{-1}	Assumed same as felled forest (Fearnside 1996b, p. 611)
Above-water decay rate (8-10 yr)	-0.0848	fraction yr^{-1}	Assumed same as felled forest (Fearnside 1996b, p. 611)
Above-water decay rate (>10 yr)	-0.0987	fraction yr^{-1}	Assumed same as felled forest (Fearnside 1996b, p. 611)
Carbon content of wood	0.50		Fearnside et al. (1993)
Rate of wood fall from above-water zone	0.1155	fraction yr^{-1}	Assumption: average lifetime = 6 yr
Average total biomass of forest at Tucurui	519	t ha^{-1}	Revilla Cardenas et al. (1982)
Average water depth at minimum level	9.7	meter	Uses 58.0 m above msl as minimum normal operating level (Brazil, ELETRONORTE, 1989, p. 64).
Initial biomass present: leaves	8.8	t ha^{-1}	Calculated from total biomass and Fearnside (1995, p. 12).
Initial biomass present: wood above water	291.0	t ha^{-1}	Calculated from total biomass and Fearnside (1995, p. 12).
Initial biomass present: below ground	125.1	t ha^{-1}	Calculated from total biomass and Fearnside (1995, p. 12).
Methane release by termites	0.687	kg CH_4 ha^{-1} yr^{-1}	Martius et al. (1996, p. 527).

Table 2: AVAILABLE DATA ON EMISSIONS FROM THE TUCURUÍ RESERVOIR SURFACE IN DIFFERENT HABITATS

Habitat	Date	Season (water level)	Season (water flow)	Emission type	Emission (mg CH4/ m2/day)			Source
					mean	sd	n	
HABITAT DIVISIONS USED IN CALCULATION:								
Open water	May 1996	High	High	Bubbling+diffusion	12			(a)
	Aug. 1996	High	Low	Bubbling+diffusion	33.5			(a)
	Dec. 1996	Low	Low	Bubbling+diffusion	65			(a)
	Aug. 1997(b)	High	Low	Bubbling+diffusion	86.5			(c)
Mean: high water flow					12.0		1	
Mean: Low water flow					61.7	26.6	3	
Macrophyte beds	May 1996	High	High	Bubbling+diffusion	73			(a)
	Aug. 1996	High	Low	Bubbling+diffusion	63			(a)
	Dec. 1996	Low	Low	Bubbling+diffusion	72			(a)
Mean: high water flow					73		1	
Mean: Low water flow					67.5	6.4	2	
Standing dead trees	May 1996	High	High	Bubbling+diffusion	56.4			(a)
	Aug. 1996	High	Low	Bubbling+diffusion	59			(a)
	Dec. 1996	Low	Low	Bubbling+diffusion	960			(a)
	Aug. 1997	High	Low	Bubbling+diffusion	74.8			(d)
Mean: high water flow					56.4		1	
Mean: Low water flow					364.6	515.7	1	

OTHER MEASUREMENTS:

Open water	Mar. 1989	High	High	Bubbling	0	(e)
	Sept. 1993(f)	Low	Low	Bubbling	0.018	(g)
	Mar.1993(h)	High	High	Bubbling	14.2	(g)
	Sept. 1993(h)	Low	Low	Bubbling	3.3	(g)
Macrophyte beds	Sept. 1993	Low	Low	Bubbling	19.0	(g)
Standing dead trees	Mar. 1993	High	High	Bubbling	3.3	(g)
	Sept. 1993	Low	Low	Bubbling	24.8	(g)
Weighted averages	Feb.-Mar. 1993	Low	High	Bubbling+diffusion	5.6	(i)
for whole reservoir	Sept. 1993	Low	Low	Bubbling+diffusion	15.8	(i)
	1998 (j)	?		Bubbling	13.1	(k)
	1998 (j)	?		Diffusion	192.2	(k)
	1999 (j)	?		Bubbling	2.4	(k)
	1999 (j)	?		Diffusion	12.2	(k)

(a) E.M.L.M. Novo, personal communication 1999.
(b) Open water: "tributaries" < 10 m depth.
(c) de Lima et al. nd.
(d) de Lima and Novo 1999.
(e) Rosa et al. 1996b,c 1997a.
(f) Open water: channel.
(g) Rosa et al. 1997a: 48.
(h) Open water: protected cove.
(i) Matvienko and Tundisi 1996: 10.
(j) Month unspecified.

(k) Matvienko et al. 2000.

Table III

Calculated areas of habitats in the Tucuruí reservoir in 1988

Month	Mean streamflow (10^3 m^3 s^{-1}) (a)	Residence time (days) (b)	Volume (10^9 m^3)	Macrophyte area (km^2) (c)	Water without macrophytes (km^2)	Exposed drawdown area (km^2)	Permanently flooded with emergent trees (km^2)	Water without trees or macrophytes (km^2)	Macrophyte area as % of total area	Macrophyte area as % of water area
Jan.	15.3	37	48.9	151.6	1,879.8	398.0	396.8	1,483.0	6.2	7.5
Feb.	20.8	27	48.5	151.6	1,879.8	398.0	396.8	1,483.0	6.2	7.5
Mar.	24.3	23	48.3	252.7	1,924.0	252.7	396.8	1,527.2	10.4	11.6
Apr.	23.8	24	49.4	252.7	1,924.0	252.7	396.8	1,527.2	10.4	11.6
May	15.3	37	48.9	505.4	1,924.0	0.0	396.8	1,527.2	20.8	20.8
Jun.	7.7	74	49.2	505.4	1,924.0	0.0	396.8	1,527.2	20.8	20.8
Jul.	4.5	126	49.0	505.4	1,924.0	0.0	396.8	1,527.2	20.8	20.8
Aug.	3.2	177	48.9	505.4	1,924.0	0.0	396.8	1,527.2	20.8	20.8
Sep.	2.4	236	48.9	151.6	1,879.8	398.0	396.8	1,483.0	6.2	7.5
Oct.	2.7	210	49.0	151.6	1,879.8	398.0	396.8	1,483.0	6.2	7.5
Nov.	4.6	123	49.0	151.6	1,879.8	398.0 (d)	396.8	1,483.0	6.2	7.5
Dec.	8.8	64	48.7	151.6	1,879.8	398.0	396.8	1,483.0	6.2	7.5
Mean	11.1	96.5	48.9	286.4	1,901.9	241.1	396.8	1,505.1	11.8	13.1

(a) Brazil, ELETRONORTE (1989, p. 51).
(b) Brazil, ELETRONORTE (1988, p. 87).
(c) In 1989 the macrophyte maximum was in July, when water level was 72 m above msl, and minimum was in November when water level was 68 m above msl (Novo and Tundisi, 1994, p. 150). Intervening months are interpolated based on the assumptions of Novo and Tundisi (1994).
(d) From Novo and Tundisi (1994, p. 149); Fearnside (1995, p. 13) used 858 km^2 based on water volumes.

TABLE IV

Methane sources in the Tucuruí reservoir surface

	High-water area (km^2)	Average area (km^2)	Share of average area (%)	Average area (km^2)		Emission (mg CH_4 m^{-2} day^{-1})		Emission (t CH_4)		
				High flow (Jan-May)	Low flow (Jun-Dec)	High-flow period (a)	Low-flow period (a)	High-flow period 151 days	Low-flow period 214 days	Total 365 days
Open water										
No trees or macrophytes	1,545.5	1,505.1	68.8	1,509.5	1,502.0	12.0	61.7	14,055	19,819	33,873
Standing tree area	407.4	396.8	18.1	396.8	396.8	56.4	364.6	21,844	30,958	52,802
Open water total	1,952.9	1,901.9	86.9	1,906.3	1,898.7				50,777	86,675
Macrophyte beds	294.1	286.4	13.1	262.8	303.2	73.0	67.5	2,679	4,380	7,059
Whole reservoir	2,247.0	2,188.3	100.0	2,169.1	2,202.0			38,578	55,157	93,734
Average emission		114.3				117.8	117.1			

(a) Table II.

Table V

Calculation of methane export by the Tucuruí turbines in 1991 (a)

Month	Turbine flow (b) (10^9 m^3)	Water level (c) (m above msl)	Correction for seasonal oscillation (%) (d)	Turbine intake depth (m below surface)	Corrected CH_4 concentration in water released by turbines (e) (mg CH_4 $liter^{-1}$)	CH_4 exported by turbines (10^6 t)
Jan.	10.9	67.5	-17	30.9	6.2	0.0676
Feb.	12.4	67.5	-33	30.9	5.0	0.0622
Mar.	12.4	69.3	-50	32.7	3.8	0.0464
Apr.	12.4	69.3	-33	32.7	5.0	0.0622
May	12.4	72.0	-17	35.4	6.2	0.0770
Jun.	9.4	72.0	0	35.4	7.5	0.0702
Jul.	9.4	72.0	17	35.4	8.8	0.0821
Aug.	6.3	72.0	33	35.4	10.0	0.0632
Sep.	4.8	67.5	50	30.9	11.3	0.0542
Oct.	4.8	67.5	33	30.9	10.0	0.0481
Nov.	9.4	67.5	17	30.9	8.8	0.0821
Dec.	9.4	67.5	0	30.9	7.5	0.0702
Mean	9.5	69.3	0	32.7	7.5	0.0655
Total	113.8					0.7854

(a) Based on 1991 power generation and 1988 storage changes and evaporation (from water and macrophyte areas).
(b) Allocated among months by adding or subtracting from average monthly mean in units of one turbine, so as to maintain positive spillway flow, within the constraints of turbine capacity and total annual electricity generation.

(c) Based on areas (Table 3), interpolated from 10-m intervals (Brazil, ELETRONORTE, 1989, Fig. MT-TUC-05).
(d) Percentage deviation from annual average based on approximate amplitude of oscillations at Petit-Saut from Galy-Lacaux et al. (1999).
(e) Corrected for spillway depth with adjustment for annual mean CH_4 concentration at the turbine depth (Fig. 2) and for seasonal oscillations in CH_4 concentration. For example, in January the annual mean CH_4 concentration for >30 m depth is 7.5 mg CH_4 liter^{-1} and the corrected concentration (-17%) is 6.2 mg CH_4 liter^{-1}.

TABLE VI

Calculation of methane export by the spillway in 1991(a)

Month	Inflow (10^9 m^3) (b)	Evapora-tion (10^9 m^3) (c)	Storage change (10^9 m^3) (d)	Spillway flow (10^9 m^3) (e)	Spillway depth (m below surface) (f)	Annual mean CH_4 concen-tration at spillway depth (mg CH_4 $liter^{-1}$) (g)	Corrected CH_4 concentration in water released by spillway (mg CH_4 $liter^{-1}$) (h)	CH_4 exported by spillway (10^6 t)
Jan.	41.0	0.26	0.2	29.7	15.5	2.6	2.2	0.0648
Feb.	55.8	0.26	-0.4	43.5	15.5	2.6	1.8	0.0767
Mar.	65.1	0.28	-0.2	52.7	17.3	3.1	1.5	0.0813
Apr.	63.8	0.28	1.0	50.1	17.3	3.1	2.1	0.1035
May	41.0	0.31	-0.4	28.7	20.0	3.7	3.1	0.0894
Jun.	20.6	0.31	0.2	10.8	20.0	3.7	3.7	0.0403
Jul.	12.1	0.31	-0.2	2.5	20.0	3.7	4.4	0.0111
Aug.	8.4	0.31	-1.2	2.9	20.0	3.7	5.0	0.0145
Sep.	6.3	0.26	-0.1	1.3	15.5	2.6	3.9	0.0050
Oct.	7.1	0.26	0.6	1.5	15.5	2.6	3.5	0.0052
Nov.	12.3	0.26	0.5	2.2	15.5	2.6	3.1	0.0067
Dec.	23.6	0.26	-0.1	14.1	15.5	2.6	2.6	0.0370
Mean	29.7	0.28	0.0	20.0	17.3	3.1	3.1	0.0446
Total	357.0	3.39	0.0	239.8				0.5353

(a) Based on 1991 power generation and 1988 storage changes and evaporation (from water and macrophyte areas).
(b) Based on long-term streamflow (Table 3).
(c) Evaporation without macrophytes is 1548 mm $year^{-1}$ (Brazil, ELETRONORTE, 1989, p. 47); evapotranspiration of macrophyte areas is assumed to be twice this rate.
(d) Based on storage volumes (Table 3).

(e) Calculated by difference from inflow and evaporation + turbines (from Table 5) + storage change.
(f) Based on water levels from Table 5.
(g) Figure 2, using values for the spillway depth with adjustment for seasonal oscillations in CH_4 concentration.
(h) Adjusted with correction for seasonal oscillations in CH_4 concentrations from Table 5.

TABLE VII

Net emissions from loss of living forest sources and sinks (a)

Item	Per-hectare flux: Gas (t gas ha^{-1} yr^{-1})	Per-hectare flux: Equivalent carbon (t CO_2-equivalent C ha^{-1} yr^{-1})	Tucuruí emission (10^6 t CO_2-equivalent C yr^{-1})	Source of per-hectare value
Loss of CO_2 carbon uptake from standing forest	1.2	0.3	0.06	Tian et al. (1998) (b)
Loss of N_2O emission from forest soil	-0.0087	-0.734	-0.14	Verchot et al. (1999, p. 37).
Loss of CH_4 uptake from forest soil	0.0005	0.00015	0.000028	Keller et al. (1986).
Loss of CH_4 emission from forest termites	-0.014	-0.104	-0.020	Fearnside (1996b).
Total		-0.52	-0.10	

(a) Considering area of lost forest as 1926 km^2 (Fearnside, 1995, p. 11). IPCC SAR 100-year global warming potentials are used: CO_2 = 1, CH_4 = 21, N_2O = 310 (Schimel et al., 1996). Negative values represent reduced emission to the atmosphere when forest is lost.
(b) Based on modeled 1980-1994 average.

TABLE VIII

Greenhouse gas emissions from Tucuruí in 1990 (a)

Gas	Emission source	Flux (10^6 t gas)		CO_2-equivalent C (10^6 t C) (b)		Relative contribution (%)	
		High scenario	Low scenario	High scenario	Low scenario	High scenario	Low scenario
CH_4	Bubbling + diffusion	0.0937	0.0937	0.537	0.537	5%	8%
	Above-water decay (c)	0.0005	0.0005	0.003	0.003	0.03%	0.04%
	Loss of forest soil sink	0.0001	0.0001	0.001	0.001	0.01%	0.01%
	Loss of forest termites	-0.0027	-0.0027	-0.015	-0.015	-0.15%	-0.22%
	Turbines	0.7025	0.1649	4.023	0.945	40%	13%
	Spillway	0.5353	0.5353	3.066	3.066	30%	44%
	Total CH_4	1.3294	0.7919	7.61	4.54	75%	64%
CO_2	Above-water decay	9.34	9.3400	2.55	2.55	25%	36%
	Below-water decay	0.11	0.1100	0.03	0.03	0.30%	0.43%
	Loss of uptake from forest	0.23	0.2300	0.06	0.06	1%	1%
	Total CO_2	9.68	9.68	2.64	2.64	26%	38%
N_2O	Loss of forest soil source	-0.00167	-0.00167	-0.14	-0.14	-1%	-2%
Total				10.11	7.03	100%	100%

(a) Components are from various years: habitat areas and water levels from 1988, per-area bubbling and diffusion from 1996-1997, turbine and spillway water flow from 1991, CH_4 content of water from 1989, decay emissions from 1990.
(b) Global warming potential of CH_4 = 21; N_2O = 310 (Schimel et al., 1996).
(c) Fearnside (1995) based on above-ground decay in forest felled for agriculture and ranching (Martius et al., 1996).

TABLE IX

Comparison with other estimates of greenhouse gas emissions from Tucurui

Author	Year of emission	Factors included (a)	CH_4 flux per unit area (mg CH_4 m^{-2} day^{-1})	Net annual emission (10^6 t gas)			CO_2-equivalent C (10^6 t C yr^{-1})	Method for CH_4 estimate
				CO_2	CH_4	N_2O		
This study: Low scenario	1990	1,2,3,4,5,6,7			9.7	0.79 -0.00167	7.0	(b)
This study: High scenario	1990	1,2,3,4,5,6,7			9.7	1.33 -0.00167	10.1	(b)
Fearnside, 1995	1990	(1,2,3), 4		9.5	0.09	--	3.1	(c)
Rosa and Schaffer, 1995	1990	(1,2,3)			--	0.52 --	3.0	(c,d)
Novo and Tundisi, 1994	1988	1,2		96	--	0.085 --	0.49	(b)
Rosa et al., 1996c, 1997b	1993	1		15	--	0.013 --	0.07	(b,e)
Matvienko et al., 2000	1998-99	1,2		112	--(f)	0.099 --	0.57	(b,e)
Matvienko and Tundisi, 1997	Sep.1993	1,2		15	--(f)	0.013 --	0.08	(b,e)

(a) Factors: 1 = bubbling from surface, 2 = diffusion from surface, 3 = turbines, 4 = above-water decay, 5 = forest soil CH_4, 6 = forest soil N_2O, 7 = forest termites; parentheses ( ) = implicitly included.
(b) Based on flux data.
(c) Based on assumptions regarding rates of decomposition and fraction emitted as CH_4.
(d) CH_4 emission calculated for 1990 from assumptions of Rosa and Schaffer (1995, p. 155) as mean of two scenarios, and converted to CO_2-equivalent C using the IPCC 100-year GWP of 21 (Schimel et al., 1996).
(e) Reservoir emissions calculated from reported per-m^2 value using an area of 2430 km^2.

(f) CO_2 bubbling measured, but cannot be considered a net emission because much is derived from carbon input from the watershed and from primary production in the reservoir.

Fig. 1

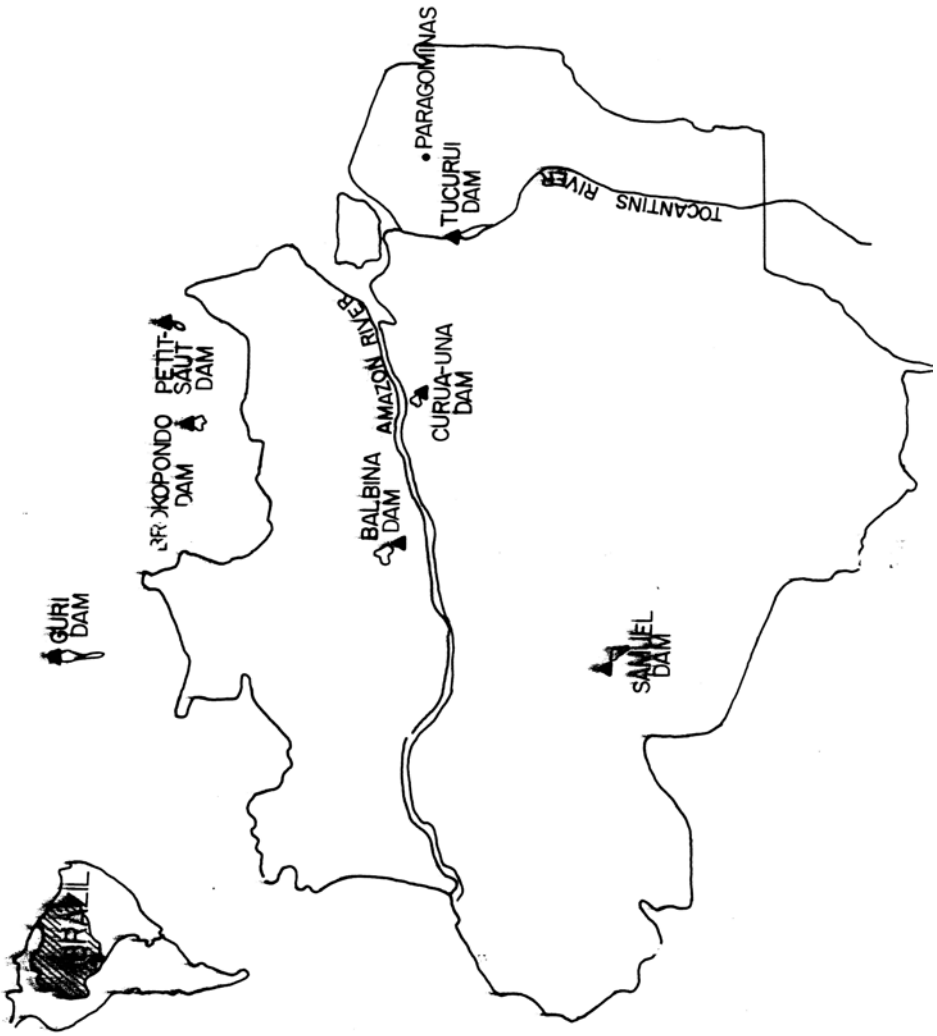
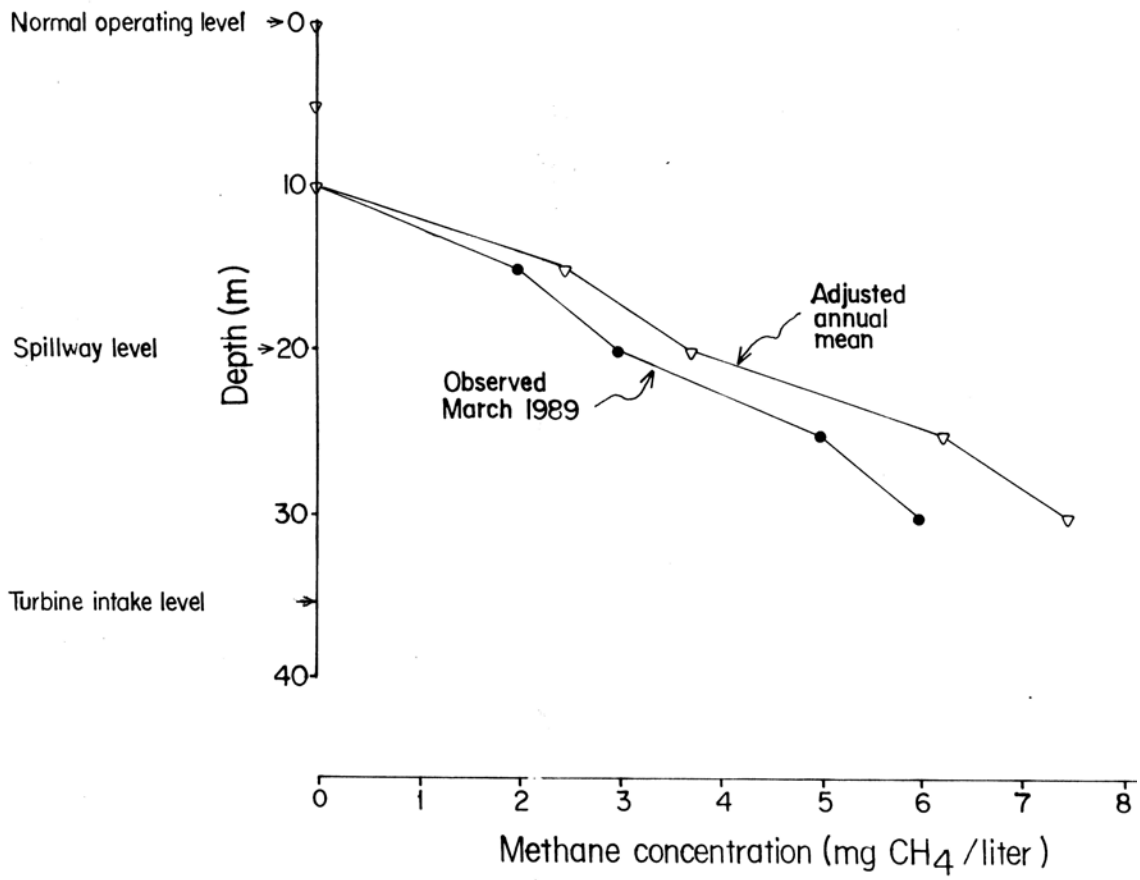

PARAGOMINAS
TUCURUI DAM
TOCANTINS RIVER
CURUA-UNA DAM
AMAZON RIVER
BALBINA DAM
PETIT-SAUT DAM
KOPONDO DAM
CURI DAM
SAMUEL DAM
BRAZIL

Fig. 2


Normal operating level
0
10
Spillway level
20
30
Turbine intake level
40
Depth (m)
Adjusted annual mean
Observed March 1989
0
1
2
3
4
5
6
7
8
Methane concentration (mg CH4 /liter)