Greenhouse Gas Emissions from Amazonian Hydroel… Reservoirs: The Example of Brazil's Tucuruí Dam[1]

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ABSTRACT

Hydroelectric dams in tropical forest areas emit carbon dioxid… methane. How these emissions and their impacts should be calculated, an… comparisons should be made with global warming contributions of alter… energy sources such as fossil fuels, can lead to sharp differences in conclusi… the relative advantages of these options. The example of Brazil's Tucurui … examined to clarify these differences.

Factors included in calculating emissions for Tucurui include the initia… stock and distribution of carbon, decay rates and pathways (leading to carbon dioxide and methane), and losses of power in transmission lines. Facto… no… considered include forest degradation on islands and reservoir shores, n… ou… oxide sources in drawdown zones and transmission lines, additional me…ane emission pathways for release from standing trees, water passing throug… the turbines, etc. Construction-phase emissions are also not included; neith… emissions from deforestation by people displaced by and attracted to the pr…ct. A complete accounting of the alternative landscape is also lacking. Standardization of the level of reliability of the electricity supply is needed to compare hydroelectric and thermoelectric options.

Types of emissions calculations include the ultimate contribut… emissions, the annual balance of emissions in a given year (such as 1990… an… emissions over a long time horizon (such as 100 years). The timing of emi… differs between hydroelectric and thermal generation, hydro producing a …rge pulse of carbon dioxide emissions in the first years after filling the reservoi… while thermal produces a constant flux of gases in proportion to the power gen…ated. The impacts of emissions are related to the atmospheric load (stocks) of the gase… rather than to the emissions (flows), and therefore lasts over a long time. According to the calculations in the present paper, the average carbon dioxide molecule in the atmospheric load contributed by Tucuruí was present in the atmosphere 15 years earlier than the average molecule in the comparabl… loa… from fossil fuel generation. This means that, considering a 100-year time h…izon, a ton of CO_2 emitted by Tucuruí has 15% more global warming impact tha… a ton emitted by fossil fuel, assuming no discounting. If discounting is applie… then the relative impact of the hydroelectric option is increased.

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Time preference, either by discounting or by an alternative procedure, is a y factor affecting the attractiveness of hydroelectric. At low annual discount rates ay 1-2%) the attractiveness of Tucuruí , although less than without discounting, is ll 3-4 times better than fossil fuel generation. If the discount rate reaches 15%, situation is reversed, and fossil fuel generation becomes more attractive from a obal warming perspective. Tucuruí, with a power density (installed pacity/reservoir area) of 1.63 W/m^2 is better than both the 0.81 W/m^2 average for razilian Amazonia's 5.5 X 10^3 km^2 of existing reservoirs and the 1 W/m^2 estimated Brazil's electrical authorities as the average for all planned hydroelectric velopment in the region.

Introduction

Hydroelectric dams in tropical forest areas emit greenhouse gases such as rbon dioxide (CO_2) and methane (CH_4). How these emissions and their impacts ould be calculated, and how comparisons should be made with global warming ntributions of other energy sources such as fossil fuels, is a matter of sagreement.

The proportion of the carbon in the decomposing biomass that is emitted as ethane rather than carbon dioxide strongly influences the global warming impact reservoirs. Per ton of carbon, methane is much more potent than carbon dioxide provoking the greenhouse effect. The average lifetime of methane in the nosphere is much shorter than that of carbon dioxide: 14.5 years versus 125 years, en a constant composition atmosphere as assumed by the Intergovernmental nel on Climate Change (IPCC) (Albritton *et al.*, 1995: 222).

The present paper examines the example of Brazil's Tucuruí Dam in order to arify differences among various approaches to this problem. I stress that the intent not to portray Tucuruí as typical of either existing or planned Amazonian dams. ucuruí is better, from a greenhouse gas perspective, than either the average isting dam or the average planned dam, but it does not represent an extreme case. nsidering official values for reservoir areas, Tucuruí has 1.63 watts (W) of stalled capacity per square meter (m^2) of reservoir surface, whereas ETROBRÁS (Brazil's national electrical authority) considers the average power nsity for the entire hydroelectric potential of the Amazon Region to be only 1 $/m^2$ (Rosa *et al.*, 1996a: 6). The equivalent figure for the 5537 km^2 of water surface the four existing large dams (whose total installed capacity is 4490 MW) is 0.81 $/m^2$, or only half the power density of Tucuruí.

The 2247 km^2 Tucuruí Dam was closed in 1984 on the Tocantins River, and ame the first major hydroelectric project in Brazilian Amazonia (*Figure 1*). Only 72 km^2 Curuá-Una Dam, closed in 1977, had preceded it in the region. bsequently dams were closed in 1987 at Balbina (3147 km^2) and in 1988 at muel (465 km^2) (areas from LANDSAT imagery, see Fearnside, 1995). Planned ervoirs listed in Brazil's 2010 Plan total, irrespective of the expected date of construction, 100,000 km², or about 20 times the present total of 5931 km Th above areas of existing reservoirs are those measured from LANDSAT imag an differ slightly from 'official' values (Fearnside, 1995: 11).

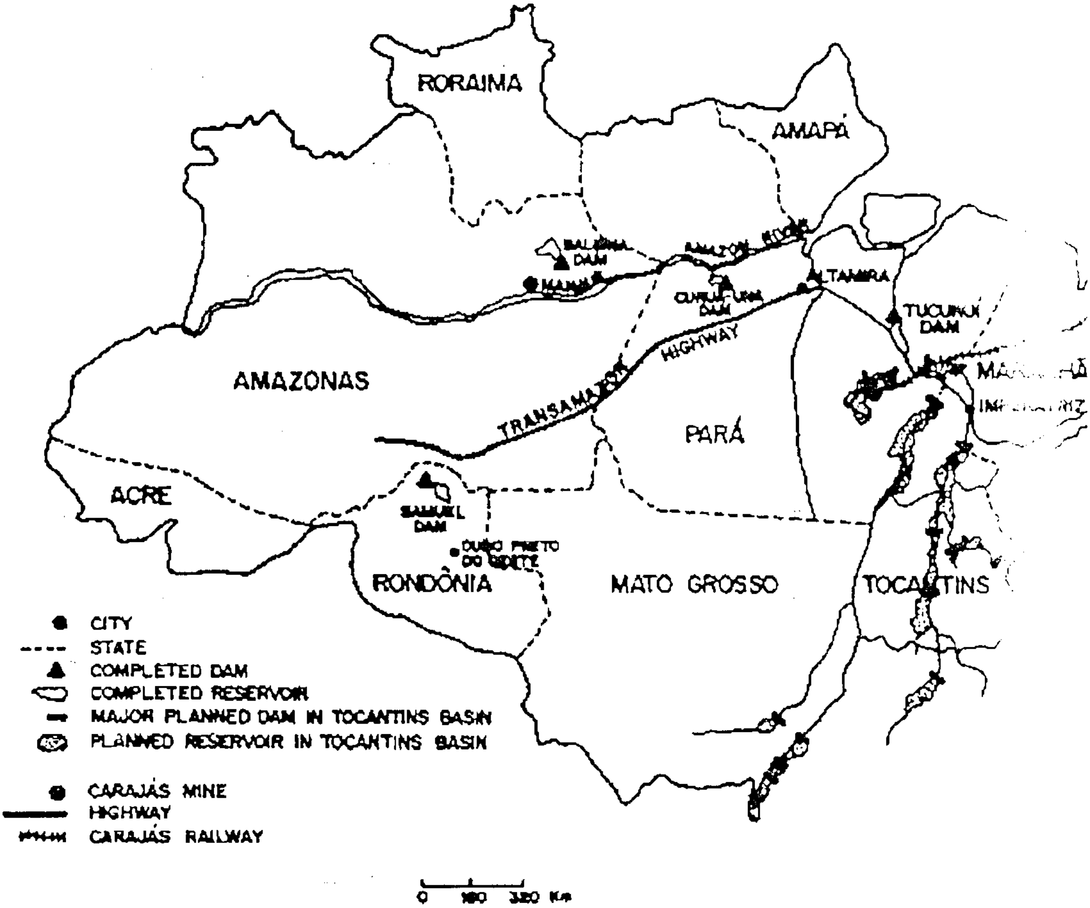

Figure 1. Brazil's Legal Amazon Region.

2. Factors Included in Calculating Emissions for Tucuruí

A. Initial Stock and Distribution of Carbon

Tucuruí's official area at an elevation of 72 m above mean sea level (msl) is 2430 km^2 (Brazil, ELETRONORTE, nd[1987]: 24-25), a value close to the 2247 km^2 LANDSAT measured area in 1989 (Fearnside, 1995). ELETRONORTE, Brazil's state power monopoly for northern Brazil, built and operates the Tucuruí Dam. The riverbed area was 321 km^2, considering a reservoir length of 170 km and an average width of 1891 m estimated by the author from 1:1,000,000-scale side-looking airborne radar (SLAR) imagery (Brazil, Projeto RADAMBRASIL, 1981). Considering the LANDSAT-measured water surface area, minus the riverbed area and the previously deforested area (ignoring any pre-flooding deforestation not done by ELETRONORTE), the area of forest loss to flooding was 1926 km^2. The 100 km^2 cleared by ELETRONORTE in the reservoir area also resulted in greenhouse gas emissions (not considered here). Reservoir filling lasted from 6 September 1984 to 20 March 1985.

Areas of different forest types and the biomass of each were estimated by the National Institute for Research in the Amazon (INPA) as part of the environmental studies contracted by ELETRONORTE (Revilla Cardenas *et al.*, 1982: 90). The area-weighted average above-ground biomass is 394 t/ha (oven dry-weight), while the approximate total biomass is 517 t/ha.

The drawdown depth is 14 m (Brazil, ELETRONORTE, nd[1992]: 5), and the average depth of the reservoir at the minimum water level can be calculated to be 9.7 m. This uses 58.0 m above msl as minimum normal operating level (Brazil, ELETRONORTE, nd[c. 1983]. A minimum operating level of 51.6 m (Brazil, ELETRONORTE, nd: 21); Brazil, ELETRONORTE, (nd[1992]) 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, nd[c. 1983]: 6).

The area of forest flooded at the operating level is 192,553 ha, and at the minimum water level is 106,787 ha (see Fearnside, 1995: Table V). Of the area cleared prior to flooding, 8000 ha is assumed to be in the permanently flooded zone and 2000 ha in the seasonally flooded zone.

Logging removals prior to flooding were small, as the contract for logging the area made with CAPEMI (a military pension fund without experience in the timber sector) ended in a financial scandal without having progressed to a state to significantly affect the biomass present (see Fearnside, 1990). Of the above-ground biomass, 1% was assumed to have been removed (Fearnside, 1995). Tucuruí has been known for the underwater logging activity initiated in 1988 using a specially developed underwater chainsaw. However, negotiations to use biomass from this source on a wide scale to supply charcoal to pig iron smelters in the Grande Carajá s Program area have broken down. Nevertheless, the present calculation assumes that between 1988 and 2000, half of the biomass is removed.

B. Decay Rates and Pathways

In order to calculate emissions from hydroelectric reservoirs one must know the amounts of biomass present and likely paths by which it will decay. Trees 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 water, produce only CO_2. The biomass above water eventually falls into the water, thereby being transferred to anoxic environments where decay is much slower-but also more likely to yield methane. Leaves and vines fall off the trees very quickly, and branches and trunks fall at a much slower rate.

The reservoir can be divided into different zones, where aerobic and anoxic conditions will have different relative importance (Fearnside, 1995: Fig. 3). 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 is located between the minimum and maximum normal operating levels will also be exposed to aerobic conditions.

The biomass can be allocated into zones (following Fearnside, 1995: Table V) using the vertical distribution of biomass in forest studied near Manaus by Klinge and Rodrigues (1973, see Fearnside, 1995: Table IV). Based on the proportion of biomass in vertical strata, the water depths at minimum and maximum operating levels, and the areas in each zone, the biomass is calculated 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), and below-ground wood. The progression of biomass values is calculated for each year, zone and biomass component. This is done using rates of decay in each zone and rates of biomass falling from the above-water to the below-water zones. The parameters used for calculating emissions from Tucuruí are summarized in Table 1 (adapted from Fearnside, 1995: Table VI). Emissions of methane from decomposition of original forest biomass are based on Table 1.

Table 1. In the end of this paper

The initial biomass present is estimated at 291.4 t/ha of wood in the above-water zone, 5.33 t/ha of wood in the surface water zone (to 1-m depth at the minimum water level), 55.47 t/ha of wood and other non-wood components in the anoxic water zone, and 122.69 t/ha of below-ground wood. The above-water and below-ground zones cover the entire forested part of the reservoir (1926 km^2), while the surface water and anoxic water zones (using averaged values for depth) cover the forested portion of the permanantly flooded zone (858 km^2).

A small methane emission is also calculated from termites in the decomposition of wood projecting out of the water (following Martius *et al.*, 1996). This is limited by the population of termites that is able to establish itself before the biomass is removed through other processes.

Methane is also produced from the "water" in hydroelectric dams, representing that coming from dissolved carbon, soil organic matter, and decomposition of macrophytes and other organisms. Since measurements for such emissions are lacking, a value derived from studies in Amazon floodplain (*várzea*) lakes is used instead (see Fearnside, 1995: Table VIII). This is 53.9 mg CH_4/m^2/day for open water and 174.7 mg CH_4/m^2/day for macrophyte beds. Tucuruí is assumed to be 90% open water and 10% macrophyte beds. LANDSAT-based measurements by de Novo and Tundisi (1994: 149) indicated that the Tucuruí reservoir was 67% open water, 22% emergent dead trees and macrophytes, and 11% seasonally flooded area. These authors derived a methane emission estimate for the reservoir by multiplying these areas by values for emissions per unit of area from measurements made by Bartlett *et al.* (1990) in similar habitats in *várzea* lakes. The methane flux rates used in the present study are slightly lower, based on the Bartlett *et al.* (1990) results averaged with other available measurements from *várzea* lakes (Fearnside, 1995: 15).

C. Transmission Losses

Transmission loss must be included in any calculation to have a fair comparison of hydroelectric with fossil fuel energy. Thermoelectric plants generate electricity at the site where it will be used, and losses from its local distribution networks can be assumed to be equal to those from local distribution of hydropower. The long-distance transport from the hydroelectric site to the point of consumption applies only to hydro, and must be considered. In the present calculation a loss of 2.5% is used, this being the low value assumed in the viability study of the Balbina Dam (Brazil, ELETRONORTE/MONASA/ENGERIO, 1976). Tucuruí has 743 km of 500-kilovolt (kV) transmission line and 75 km of 230-kV line (not counting the approximately 500 km 500-kV line segment from Imperatriz to São Luís) (Brazil, ELETRONORTE, nd[*c.* 1983]). The total is thus over four times the length of Balbina's 190-km 230-kV line, but transmits much larger volumes of energy. Transmission losses were not included in the calculations for 1990 in Fearnside (1995).

3. *Factors Not Considered In The Present Calculation*

A. *Sources of Direct Emissions*

1. Forest Degradation on Islands and Shores

Forest on islands and on the reservoir's shores are subjected to stress from the raised water table, causing many individual trees to die and depleting the forest's biomass. Forest degradation on islands also occurs due to the effect of fragmenting forest into small isolated patches (*e.g.* Lovejoy *et al.*, 1984).

II. Nitrous Oxide Sources

Nitrous oxide (N_2O) is probably released from soils exposed in the seasonally flooded zone during drawdown periods. This is not included in the present calculations. Some N_2O is formed in the air by high-voltage transmission lines. Quantification of nitrous oxide is important because of the high impact of this gas on global warming relative to CO_2; its 100-year integration global warming potential (GWP) is 320 relative to CO_2 on a mass basis (Albritton *et al.*, 1995: 222).

III. Additional Methane Emission Pathways

The processes by which methane is released are not well quantified, and could significantly increase the amount of these emissions above what has been calculated in the present paper. Emissions here have been estimated based on different processes. For emissions from the "water," this is on the basis of available information on emission from the water surface of várzea lakes. However, much of the methane is oxidized to CO_2 in the water column before being released at the surface. Processes unique to reservoirs that would allow methane to be released directly, without passing through the full water column, would substantially increase emissions over this estimate. One such contribution is CH_4 released when water passes through the turbines, taking anoxic water and abruptly decreasing its pressure. With an average streamflow of 11.1 X 10^3 m^3/s, Tucuruí's volume of 48 X 10^9 m^3 of water turns over every 50 days (0.138 years). Marc Lucotte (personal communication) found only a few percent of the total methane release to occur through water passed through the turbines of the 15,000 km^2 La Grande complex in Quebec, Canada. However, because La Grande has such a large area, and because its turnover time is on the order of one year, the relative importance of water surface would be greater than at Tucuruí . The reason is the same as that causing natural lakes, in general, to have greater contribution from wind and surface diffusion than do reservoirs (see Baxter, 1977: 259).

The amount of methane emitted by the reservoir depends heavily on the routes available through which methane in anoxic water at the reservoir bottom can reach the surface without being oxidized to CO_2 in the water column. The present calculation considers only diffusion through the water surface at a rate assumed to be equal to that occurring in *várzea* lakes. Individual events that bring anoxic water to the surface would not be captured by these quite low mean rates. Cold spells (*friagens*) affect the western part of Brazilian Amazonia, not the location of Tucuruí in eastern Amazonia. Cold spells cause breakage of the thermocline and complete mixing of the water column, bringing anoxic methane-rich water to the surface where a pulse of emissions can occur. However, at Tucuruí the river channel portion reservoir has been found to be thermally stratified only in the dry season;

with the onset of rains, the great influx of oxygenated rainwater eliminates anoxic conditions in the channel during the high-water period when the turnover time is only a few weeks (Junk and de Mello, 1987: 380). In Tucuruí's stagnant bays and littoral areas where standing trees impede water flow, stratification is maintained year-round (Pereira, 1989 cited by Roulet, 1992: 52). The same applies to the Brokopondo reservoir in Surinam (Leentvaar, 1966 cited by Baxter, 1977: 261).

The methane release calculations in the present paper do not include the possible role of dead trees standing in the reservoir in serving as conduits for methane from the soil of the reservoir floor. Marc Lucotte (personal communication, 1996), has found dead trees in reservoirs in northern Canada to act in this way, with methane passing through the xylem and phloem of the dead trees allowing the gas to be released directly to the atmosphere, thereby escaping blockage by the thermocline and oxidation to CO_2 in the water column.

IV. Construction-phase Emissions

Construction of hydroelectric dams emits greenhouse gases through fuel use in excavation of earth and rock, transport of materials, and emissions in the manufacture of cement and steel. Tucuruí required 6.2×10^6 m^3 of concrete (Brazil, ELETRONORTE, nd[1992]: 5). In addition there were 55.3×10^6 m^3 of compacted clay, 20.0×10^6 m^3 of rockfill, 22.9×10^6 m^3 of rock excavation, 24.3×10^6 m^3 of ordinary excavation, and 4.7×10^6 m^3 of filters and transitions (Brazil, ELETRONORTE, nd[*c.* 1983]). For the transmission line, 1937 towers were required (not counting the Imperatriz-São Luís stretch of the line).

B. COMPLETE ACCOUNTING OF ALTERNATIVE LANDSCAPE

One must have an estimate of the emissions that would have occurred in the absence of the dam. The easiest assumption in estimating such an emission is that the landscape remained in a static state equal to that present before building the dam, but a fairer comparison would be achieved by comparing the dam with a scenario for development in the region without the dam.

Primary forest soils are natural methane sinks, and removing this sink represents a small impact on global warming. This is included in calculations of contributions of hydroelectric dams (along with deforestation) to the annual balance of net emissions in 1990 (Fearnside, 1996a), but is not included in the Tucuruí calculation in the present paper.

Possible uptake of carbon by growth of natural forest, found in the one available measurement so far (Grace *et al.*, 1995) has not been included in the calculation. Were the forest considered to be a natural carbon sink, then removing it by flooding would have greater impact on global warming.

Land-use emissions from deforestation influenced by the dam can have a significant impact on the net effect of the dam. Because the human population that was displaced by the reservoir would have continued to clear within the submergence area had the dam not been built, only the initial pulse of deforestation from this relocated population represents a real addition to deforestation emissions. Newly arrived settlers on the Transamazon Highway near Altamira (Pará) cleared at an annual rate averaging 3.6 ha/family during the first five years, while in Ouro Preto do Oeste (Rondônia), lots were cleared at an average annual rate of 2.7 ha/family during the first six years the lot is occupied, after which the clearing rate fell to very low levels until the lot was sold to a new owner (Fearnside, 1984). Logging activity that would have continued in the submergence area had the reservoir not been created was probably displaced to forests outside the submergence area, without representing a net change.

One also must deduct the CH_4 emissions that would have been produced by the water in the natural river within the stretch flooded by the reservoir. In the same way, emissions of both CH_4 and N_2O must be deducted from the seasonally flooded area (*várzea*) during the flooding and exposure stages of the river's natural hydrological regime.

C. Indirect Emissions

Known as "leakage" in discussions over the net benefits of silvicultural plantations as a global warming mitigation measure, indirect effects can substantially increase global warming impacts of a development project, including a hydroelectric dam like Tucuruí. The reservoir made it necessary to relocate a 120-km stretch of the Transamazon Highway, placing this (and its associated feeder roads) in a forested area. Tucuruí displaced 3350 families (17,319 people) according to estimates made after the reservoir had been filled (Monosowski, 1990: 32). Although some of these people moved to towns, most were moved to settlement areas where they cleared land for agricultural plots, particularly in Gleba Parakanã (on the western shore). A severe infestation of *Mansonia* mosquitoes at this site (Tadei *et al.*, 1991) has caused many of these people to subsequently move to a new area of forest, where additional area was deforested. Other people have been attracted to the area by the project and its infrastructure, and have cleared additional forest.

Not all of the emissions from clearing by the population attracted to the dam can be blamed on the project, however, as many of these people would be clearing forest elsewhere in Amazonia were it not for the dam. The same applies to emissions from urban centers that have grown as a result of the dam. Replacing urban infrastructure flooded by the dam, however, represents a direct impact. Tucuruí flooded the town of Jacundá , requiring complete rebuilding of the town at a new site (Mougeot, 1990).

A substantial effect of Tucuruí, either positive or negative, is its role in river transportation. The dam could have greatly facilitated transportation from its catchment area had shipping locks been completed. The Tocantins River formerly had rapids in the stretch of river now submerged by the reservoir. This barrier had motivated construction of a railway in 1905 (now abandoned) to bypass the rapids during Brazil's rubber boom.

In 1979 the decision was made that, simultaneously with construction of shipping locks was begun, they were abandoned before completion. Barge transport on the Tocantins River would be a less energy consuming means of exporting ore from the Carajás mine than the railway option later adopted. Carajás has the world's largest high-grade iron ore deposit with an estimated 11 X 10^9 t of ore, sufficient for mining at the current rate for 400 years. In addition to iron, the Carajás area has minable deposits of copper, bauxite and other minerals, and is associated with the Grande Carajás Program to administer an agricultural plan eventually expected to export large amounts of soybeans and other agricultural products (see Fearnside, 1986, 1989a). Ore and other products from Carajás are now exported using an 890-km railway completed in 1983. With the railway a *fait accomplis*, finishing the locks at Tucuruí came to be viewed as part of a second phase of development of Carajá s to allow expansion of exports beyond the limits imposed by the railway's capacity (Pinto, 1982: 46). It is also an option for substantially increasing agricultural exports from the Tocantins-Araguaia Basin, especially of soybeans. Should the locks be completed, then the reservoir would begin to yield an energy and carbon savings by avoiding fuel use for additional rail transport.

The capacity of the railway (30 X 10^6 t of ore/year) limits exports, which might be larger today were transportation being done by barge. Because ore at Carajá s is extraordinarily pure (66% iron), the mining of lower grade deposits elsewhere in the world (including those in Minas Gerais, Brazil), results in more GHG emissions from transportation and smelting than would be the case were this iron being supplied from Carajás.

Some possibility exists that the locks in the Tucuruí Dam may one day be completed. Although the subject is periodically raised, no specific commitment has been made, and it is therefore more realistic to calculate emissions scenarios without these facilities.

D. STANDARDIZATION OF LEVEL OF SERVICE

Comparing different types of energy generation requires decisions concerning the level of service, that is, the constancy of electricity supply, that must be supplied by each. Hydroelectric generation in Amazonia has a strong seasonal cycle of energy supply due to seasonal availability of water for power generation. Were electricity to be offered at the same level of service by both hydro and thermal options, for comparative purposes, one would have to include emissions of the backup thermoelectric generators necessary to supply power at the full rate year-round. Standardizing level of service is an accepted technique for comparing options that differ greatly in power reliability, as in the case of wind power and thermal generation.

In the case of Tucuruí a complete standardization at the peak power might be unrealistic as a representation of the real choices involved. When the services being supplied are essential, as in supplying urban centers, thermal backup is needed during low-water periods. For example, Balbina (supplying Manaus, Amazonas) is completely backed up by thermal plants. In the case of Tucuruí, however, about two-thirds of the power is used for aluminum manufacture, and it may be more economical to only smelt aluminum in proportion to available hydropower rather than to supply large amounts of more expensive supplementary power from thermal backup systems. In any case, some form of correction for thermal backup, either full or partial, is needed for a fair comparison of Tucuruí with thermal generation.

E. *Plans for Expansion and Basin Development*

The present calculation has considered only the present ("Tucuruí -I") configuration of the dam. Further increases in output (and in impacts) may occur in the future were the normal operating level increased to allow installation of more turbines. Output and impacts may also increase by construction of additional dams upstream of the first, thereby regulating the flow of the river in order to provide more water during the low-water season. The additional impacts of raising the water level and/or building additional dams would, of course, have to be taken into account.

ELETRONORTE has plans to expand the installed capacity of Tucuruí to 7960 MW in the Tucuruí -II project. ELETRONORTE has, to this author's knowledge, never released a figure for the area of the Turucuí Reservoir at an elevation 74 m above msl, the normal operating level for the Tucuruí -II project in the original plan for this addition. The result has been that a number of authors (including this one) have calculated energy density values for the full configuration of Tucuruí-II, using the area at the 72 m normal operating level adopted for the now-installed "Tucuruí-I" configuration of 3960 MW (*e.g.* Fearnside, 1989b; Goodland, 1980). ELETRONORTE has since decided that the settlers who have moved into the area along the present shoreline would make raising the water level to 74 m politically impossible, and the current plans for Tucurui-II call for maintaining the water level at 72 m (John Denys Cadman, personal communication, 1996). It is not known how much, if any, the change would reduce the amount of power that the Tucurui-II configuration could produce annually.

An indication of the additional area that would be flooded were the water level to be raised to 74 m for Tucuruí-II is given by a survey of vegetation, which considered 415.37 km^2 to be in the area expected to be flooded in the second stage (Revilla Cardenas *et al.*, 1982). Using the LANDSAT-measured area for Tucuruí-I, one can calculate that the total surface area of the reservoir were the water level raised for Tucuruí-II would be 2662 km^2. If areas used in the vegetation survey are used, the total area (forest and riverbed) would be 3047 km^2.

In addition to any flooding of more area in Tucuruí proper, the Tucuruí -II scheme would require regulating the flow of the Tocantins River by building the

Santa Isabel Dam on the Araguaia River, the first major tributary upstream of Tucuruí (Paulo Edgar Dias Almeida, personal communication, 1991). The impacts of this must therefore be considered in evaluating the Tucuruí-II proposal. ELETRONORTE has plans to build dams upstream of Tucuruí on the Tocantins and Araguaia rivers (see Junk and de Mello, 1987: 370). The impacts and benefits of these more extensive schemes would have to be evaluated together with Tucuruí. The full plan for development of the Tocantins/Araguaia basin calls for 26 dams upstream of Tucuruí.

4. *Types of Emissions Calculations*

A. *Ultimate Contribution to Emissions*

One way to approach greenhouse gas emissions from hydroelectric dams is to calculate the ultimate contribution that would occur with decomposition of all forest biomass flooded by the reservoir. This is much easier to calculate than is the impact of flooding on the annual balance of net emissions because one need not know the rate at which decomposition occurs. Rosa and Schaeffer (1995) have done a calculation for Tucuruí using a method equivalent to this approach, assuming that biomass has a half-life of only seven years and considering emissions over a 100-year time horizon without discounting. The assumptions of these authors can be used to calculate that the cumulative release over 100 years would be 2.3-5.3 X 10^6 t of CH_4, or 56.4-128.9 X 10^6 t of CO_2-equivalent gas using 1994 IPPC 100-year integration GWPs. Rosa and Schaeffer's (1995) analysis, however, assumes (without explanation of any justification) that 10-30% of the biomass decomposes anaerobically (*i.e.*, to CH_4), and considers only the impact of the methane--thereby ignoring the 70-90% of the carbon that they have assumed is released as CO_2. A valid comparison would require accounting for all gases emitted by both options (see Fearnside, 1996b and Rosa *et al.*, 1996b).

Calculation of the ultimate contribution of reservoirs to emissions, while useful as an illustration, tells us little about the contribution to the ***annual*** balance of emissions. The United Nations Framework Convention on Climate Change (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.

Junk and de Mello (1987: 381) made two calculations of the emissions of Tucuruí as compared to fossil fuel generation. In an optimistic calculation, they concluded that the quantity of carbon dioxide released from forest flooded in

Tucuruí would be emitted by generating the same amount of energy from fossil fuels in only 1.5 years. This calculation assumed that mean biomass is 300 t/ha, that no forest is cleared outside of the reservoir area, and that the dam would generate from the outset 8000 MW of power (*i.e.*, the Tucuruí-II configuration and the [impossible] load factor of 100%).

The pessimistic calculation of Junk and de Mello (1987: 381) indicated breakeven after 37 years. The latter calculation was made assuming that mean biomass is 600 t/ha, that an area outside the reservoir is cleared equal to five times the reservoir area, and that 4000 MW are generated from the outset. Both the optimistic and pessimistic calculations assumed that only half the area of the reservoir was forested, that all forest biomass carbon is emitted as CO_2, and that the thermolelectric alternative burns diesel fuel with an energy content of 10,900 kcal/kg and a conversion efficiency of 20% to electric power.

B. Annual Balance of Emissions in a Specific Year

Under the Framework Convention on Climate Change (FCCC), countries are currently undertaking national emissions inventories to assess fluxes in the year 1990-an exercise to be repeated at regular intervals for future years. Ability to assess fluxes for a specific year, such as 1990, is therefore important. The approximate quantities of biomass and emissions present in each zone in Tucuruí were calculated for 1990 (the base year for national inventories) (Fearnside, 1995: Table VII). Tucuruí's methane emission in 1990 totaled 0.09 X 10^6t CH_4 gas. Emissions of CH_4 gas from the entire reservoir were 215 t from termites, 39.8 X 10^3t from open water, 14.3 X 10^3t from macrophyte beds, and 40.2 X 10^3t from underwater decay. The underwater decay portion was composed of contributions from the permanently inundated zone of 0 t from wood in the surface water zone, 11.9 X 10^3t from wood in the anoxic water zone, 2.0 X 10^3t from leaves and other non-wood biomass in the anoxic water zone, and 10.2 X 10^3t from below-ground biomass. Contributions from the seasonally inundated zone were 13.3 X 10^3t from underwater decay of wood, 1.8 X 10^3t from leaves and other non-wood biomass, and 64 t from below-ground decay.

C. Emissions Over 100 Years

1. Timing of Emissions

Hydroelectric power has some fundamental differences from fossil fuels that make comparisons of impacts of these two options produce very different results depending on the treatment given to time in the calculation method. Fossil fuel generation produces emissions in direct proportion to energy produced, and providing a constant stream of benefits in the form of electricity will produce a constant stream of emissions. Hydroelectric dams in tropical forest areas, on the other hand, produce a large pulse of emissions in the first few years after closing, and emissions then taper off to a much lower level as the bulk of forest biomass, especially the above-water biomass, either decomposes or is transferred to the bottom of the reservoir. The benefits typically follow a pattern that is the inverse of the pattern for the impacts. Benefits begin at a low level with only a few turbines installed, and increases by steps over the succeeding several years as the remaining turbines are installed.

The initial pulse of emissions when a reservoir is flooded, particularly from CO_2 released from decay of dead trees projecting above the water, greatly exceeds the dam's global warming benefits in terms of fossil fuel substitution. Different dams vary tremendously in the time required to break even on an instantaneous basis, that is, for annual emissions to fall to a level below that required to produce the same power from fossil fuel (omitting the accumulated impacts of the initial peak of emissions).

The form of the decline in remaining biomass is important to understanding why high rates of emissions are to be expected in the first years after filling a reservoir. Because of the many tree species with differing resistances to decay, the decline is not a simple exponential described by a single decay constant. I handle this problem by dividing time into four periods and applying a different exponential decay rate in each period (Table 1). After the initial rapid decline in biomass, the amount remaining at any given time up to the end of the time horizon is greater than it would be were a single rate applied. In fact, it should be even more so than the calculations indicate due to some highly resistant species. For example, in Gatun Lake (created by the Panama Canal), some trees were still standing over 70 years after flooding (Bultman and Southwell, 1976).

Methane emissions calculated from the present assumptions are almost constant over time. However, there is some evidence that a much greater pulse of methane is emitted soon after the reservoir is filled. Tundisi (unpublished) measured CH_4 emissions with floating chambers at Samuel 0.25 years after flooding and at Tucuruí 4.5 years after flooding; these measurements have been used by Luis Pinguelli Rosa and Roberto Schaeffer (personal communication, 1996) to estimate flux rates of methane from the reservoir surface of 227 g C/m^2/year at Samuel and 0 at Tucuruí. The lack of methane emissions at the water surface at Tucuruí does not mean that the reservoir was not emitting this gas through other means, especially from water passing through the turbines.

The emissions from the Tucuruí -I phase are shown in Figure 2 over a span of 100 years. The great pulse of carbon dioxide emissions in the first years after filling the reservoir is evident. Methane, under current assumptions, is emitted at an almost constant rate over the time horizon. In Figure 3 the effect of Tucuruí and its fossil fuel equivalent are compared in terms of global warming impact of the annual emissions, as expressed in terms of CO_2-equivalents adjusted to the year of emission (*i.e.*, instantaneous without adjustment for the effects of non-simultaneous emissions over the course of a time horizon of, say, 100 years). This is done by multiplying the quantities of each gas by its 1994 IPCC 100-year integration GWP (Albritton *et al.*, 1995: 222). On this kind of instantaneous basis (*i.e.*, forgiving the

the accumulated history of emissions since the beginning of the time se
Tucuruí begins to 'break even' from the sixth year onwards. In Figures 2 a
time "0" signifies the time the power station comes on line, not the time the d
closing. Emissions from the filling phase (*i.e.*, before the dam comes on line),
emissions from construction, would be represented by negative numbers for tim

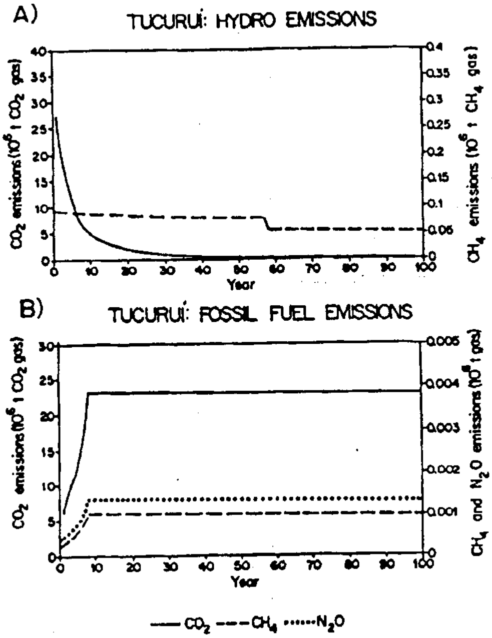

Figure 2 .Tucuruí: emissions
A) from the hydroelectric project,
B) from fossil fuel displaced by Tucuruí.

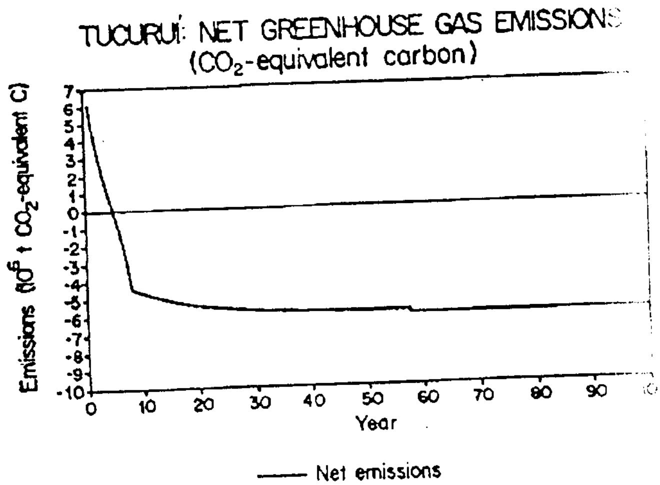

Figure 3 . Tucuruí: net greenhouse gas emissions.

2. Impacts of Emissions

The Framework Convention on Climate Change (FCCC) (Article 2) fixes attention on the *atmospheric loads* (stocks) of gases, as distinct from emissions (fluxes), temperature increases provoked by the atmospheric loads, physical changes caused this warming (increased sea levels, frequency of floods, frequency of droughts, etc.), and impacts of these events on humans (increased mortality rates and material damage). The FCCC cites "dangerous levels," of these atmospheric loads as the condition to be avoided, and is sometimes interpreted as meaning that importance is only attached to reaching distinct "threshold" values, such as the 550 parts per million by volume (ppmv) atmospheric CO_2 concentration taken as an illustration by Wigley *et al.* (1996) as the point at which atmospheric concentrations might be stabilized. This target theoretically represents the point at which the risk would be unacceptable that a drastic (*i.e.*, "dangerous," in the language of the FCCC) climatic shift might occur. The value of this threshold has not been estimated by the IPCC nor agreed upon by the parties to the FCCC. The IPCC uses scenarios ranging from 450 to 1000 ppmv as the target for stabilization (IPCC Working Group I, 1996: 3). The 550 ppmv value is approximately double the pre-industrial CO_2 level, and implies substantial impacts: models for equilibrium conditions following such a doubling indicate mean global temperatures rising 1.5-4.5°C, with a most likely value of 2.5°C (Houghton *et al.*, 1992: 16). Projections to the year 2100, including the cooling effect of industrial aerosol emissions, indicate global mean tempearature rising above the 1990 mean by 1-3.5°C, with a most likely value of 2°C (IPCC Working Group I, 1996: 6). The corresponding increase in sea level is 15-95 cm, with a most likely value of 50 cm.

Wigley *et al.* (1996) argued that it would be better to emit greenhouse gases now when we are still far from this threshold: the 1992 atmospheric CO_2 concentration was approximately 355 ppmv (Houghton *et al.*, 1995: 25), and the IPCC 'business-as-usual' (reference) scenario would bring us to 550 ppmv in approximately 2070 (Houghton *et al.*, 1995: 22). This argument, of course, assumes no discounting or other time preference weighting for short-term versus long-term impacts.

The focus on thresholds implies reduction of the threats of climatic change to that of a 'flip-flop' or discontinuity, such as an open Arctic Ocean and altered ocean current patterns, including the Gulf Stream. Although the risk of such a drastic change is, indeed, something that the precautionary principle would warn us to accept sacrifices in order to avoid, there is more to climatic change than this. Simplifying the problem to one of thresholds misrepresents the nature of risk: in addition to abrupt thresholds leading to dramatically altered climate, many of the impacts of climate change are incremental in nature. Rising sea levels, for example, increase the damage caused by hurricanes and tropical storms, such that more frequently occurring small storms take on the damage levels that formerly characterized extreme events, and extreme events take on unprecedented deadliness.

Even for global warming risks that involve abrupt discontin[illegible] thresholds, increases for GHGs below the predicted threshold have impor[illegible] policy. To a certain extent, the possibility of crossing a major threshold is an[illegible]go to pushing a ruler off a table. If the ruler is 30 cm long, one may push it un[illegible] of it extends over the edge of the table, after which any further pushing w[illegible] the ruler to tumble to the floor. If one is uncertain as to how long the [illegible] however, the probability of crossing the threshold will increase in accord [illegible] probability density profile of our knowledge about where the threshold lies.

If one considers only the FCCC's implication of keeping atmospher[illegible] below specified bounds, then economic rationality (*i.e.*, discounting) will [illegible] decisions to postpone any cutting back of emissions or implementation of m[illegible] measures. Wigley *et al.* (1996) have argued this case. These authors also po[illegible] additional advantage of delaying responses until the atmospheric load [illegible] approached: the higher atmospheric concentrations present if emissions [illegible] are delayed would accelerate uptake by some sinks, thereby allowing more G[illegible] be released, in total, over the time horizon. However, these authors also p[illegible] that the delayed cutbacks scenario implies global mean temperatures that a[illegible] by 0.2° C and global mean sea levels higher by 4 cm. A preference for [illegible] cutbacks is only indicated if impacts such as these are judged insignificant. [illegible] view such impacts as insignificant, making the earlier emission of hydroelectric, opposed to fossil fuel, generation a factor weighing *against* the hydroelectric option.

The atmospheric loads of greenhouse gases from Tucuruí are shown Figure 4-A over a time horizon of 100 years. The comparable profile for emissions from fossil fuel generation of the same power is shown in Figure 4-B. The effect the great pulse of initial emissions in the case of hydroelectric generati[illegible] maintain a higher level of carbon dioxide in the atmosphere for a period [illegible] dam begins to "break even" on an instantaneous basis (Figure 3).

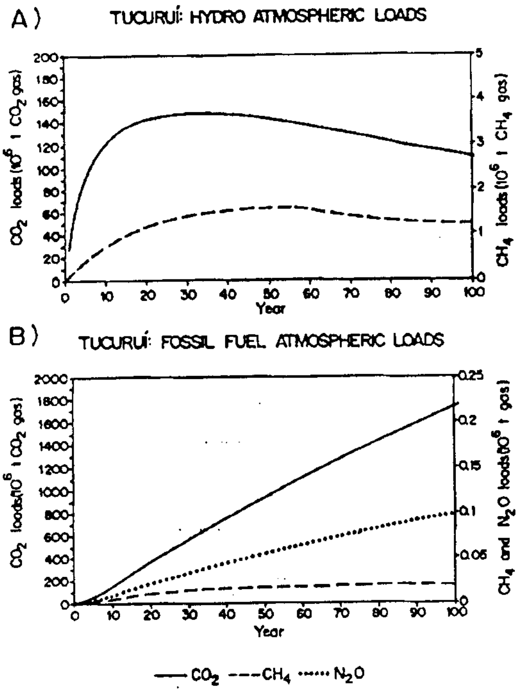

Figure 4 .Tucuruí atmospheric loads of greenhouse gases
A) from the hydroelectric project,
B) from fossil fuel displaced by Tucuruí.

The average radiatively equivalent CO_2 molecule emitted by a hydroelectric dam is present in the atmosphere earlier than the corresponding molecule emitted by fossil fuel generation. 'Radiatively equivalent CO_2' refers to equivalents of CO_2 in terms of instantaneous radiative forcing (not GWP, over a long time horizon, such as the IPCC 100-year integration GWPs). The "center of gravity" of the distribution of total radiative forcing (*Figure 5*) is year 52 for Tucuruí 's hydroelectric output, and year 67 for the fossil fuel equivalent of Tucuruí. The 15-year difference represents a significant gain in postponing global warming. The value attached to this time difference depends on the discount rate chosen (*Figure 5*). Choice of a discount rate is a moral and political decision, not a scientific one, but it must nevertheless be made. Use of a zero discount rate also represents a choice, and this must be made conscientiously. Unfortunately, the choice to use a zero discount rate is being made for society without its knowledge or consent.

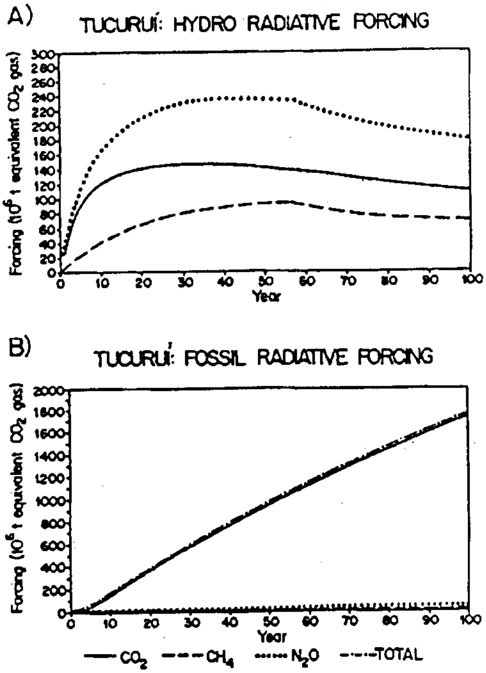

Figure 5. Tucuruí : radiative forcing of atmospheric loads of greenhouse gases A.) from the hydroelectric project, B.) from fossil fuel displaced by Tucuruí . The center of gravity of the total radiative forcing curve is at year 52 for the hydroelectric emissions and at year 67 for the fossil fuel emisions, a difference of 15 years.

The difference between the importance of a ton of GHG in the atmosphere now versus 15 years from now is the impacts of global warming caused by those gases over 15 years, such as floods and droughts. How much value society places on these impacts is a major factor in evaluating hydroelectric contributions to global warming.

Rosa and Schaeffer (1994) have proposed an alternative to the IPCC's global warming potentials such that the timing of emissions is considered, and the radiative forcing impact is only counted from the time of emissions onward. This is an advance over the IPCC method, which is based on comparison of simultaneous emission of a molecule of CO_2 and a molecule of each other gas, such as CH_4. The Rosa and Schaeffer (1994) method does not, however, include any weighting for time preference, assuming a discount rate of zero. Both features are needed: consideration of the timing of the radiative forcing (*i.e.*, the timing of the presence of the atmospheric load of gases, as distinct from the timing of the emissions), and consideration of the weight society gives to time. Rosa and Schaeffer's (1994) method also differs from the one adopted here in having different time horizons over which emissions are considered and over which the radiative effects of the atmospheric loads are considered. In the method adopted here, both end at a common point in time (100 years after closing the dam).

Both the Rosa and Schaeffer (1994) formulation and the one adopted here imply considering the different gases in a way different from that currently adopted by the IPCC. The principal justification for the GWP formulation of IPCC is that a more complicated formulation would be too difficult for policy-makers to understand (R.T. Watson, public statement, 1992). However, GWPs are, in fact, a black box from the point of view of decision-makers, who do not grasp the details of how GWPs are derived. Under such circumstances one may as well use a more complicated formulation that better reflects the importance of timing of emissions and of their impacts on radiative forcing. The new black box would be used in the same way by decision-makers, and the result would be a fairer comparison of energy options in terms of societal interests.

II. Effects of Time Preference

The question of applying discounting (or an alternative time weighting) to greenhouse gas emissions and/or their impacts is a matter of debate. The Global Environment Facility (GEF), which administers World Bank funds intended for combating global warming under Agenda 21, currently does not discount carbon or GHGs and their impacts.

Sound reasons exist for some form of time preference weighting for global warming impacts, rather than a zero-discount scheme. Buildup of greenhouse gases in the atmosphere initiates a stream of impacts (including increases in human death rates), not just single-event impacts. If this stream of impacts begins later rather than sooner, the savings (human lives, for example) between the sooner and the later time represents a permanent savings, even though the same individuals may die the next year. The logic is directly parallel to the accepted practice of considering avoided fossil fuel emissions as permanent savings, even though the same barrel of oil may be burned the next year. Applying even a very small discounting would greatly increase the impact of the large initial pulse of hydroelectric emissions relative to the evenly distributed emissions from fossil fuel.

The long atmospheric life of some greenhouse gases, particularly the 125-year average life of CO_2 (Albritton *et al.*, 1995), means that global warming impacts continue long after an emission occurs. Even were emissions to be greatly reduced, the atmospheric load remaining from past emissions would continue to provoke droughts, floods, and other impacts. These features of climatic change contribute to the rationale for some form of discounting or other time preference weighting.

Although not addressed specifically, discounting is implicit in the FCCC's emphasis on annual balance of net emissions, implying that this will be the criterion for any penalties later negotiated as protocols under the Convention. This is implied by the agreement of all countries to conduct inventories of the annual fluxes of emissions (as opposed, for example, to net committed emissions, which would capture the long-term differences between hydroelectric and thermoelectric generation). The annual balance criterion implies discounting because the countries of the world do, in fact, apply discounting when considering money. This n that, from the point of view of national planning, financial costs of the cli impacts, financial costs of mitigating measures, *and* financial costs of any fin taxes on emissions would be treated this way.

Among the implications of the annual balance criterion (and there discounting) is that delay in negotiating protocols to implant fines and si measures creates a motivation to build hydroelectric projects now rather than In this way the large pulse of emissions is not counted against the country's an balance of net emissions.

Assuming that a discount rate greater than zero is applied, the value ch would have a great influence on the energy choices indicated as preferable. Ju with the case of discounting for financial calculations, hydroelectric dams wi indicated as more attractive than thermal generation if lower discount rates are u In financial calculations, proponents of hydroelectric dams usually argue strongl lower discount rates than those used for other kinds of investments. Because o long lag times between financial investments and the initiation of revenue electricity sales, hydroelectric development would often be unattractive at higher discount rates. Hydroelectric proponents do not, however, argue for discount rates in the financial sphere. The same needs to be applied to the ben and impacts in the global warming sphere.

Birger Solberg, of the European Forest Institute, holds that the discount used for carbon must be the same as the one used for money (public statemen 1994). Dilip Ahuja, now of the World Bank, holds that the discount rate used carbon should be different (*i.e.*, lower) than that used for money (personal communication, 1992); his previous work on global warming potentials has used annual discount rate of 5% (Lashof and Ahuja, 1990).

Discount rates of 10-12% are common in financial analyses of development projects in Amazonia. Some World Bank economists have recommended using discount rates of 15% for projects in Brazilian Ama (Skillings and Tcheyan, 1979). These and other discount rates repre adjustments of real value, that is, after correction for inflation. This autho preference (Fearnside, nd-a) under an alternative time preference scheme has integral effect (the area under the time weighting curve) equivalent to an annual discount rate of 1.24%.

Discount rates in the range used for financial calculations would have dramatic effect on the attractiveness of hydroelectric generation from a glo warming perspective. The relationship of discount rate to the relative impact fossil fuel generation is shown in Figure 6. At 15% annual discount rate, fossil becomes more attractive in the case of the current calculations for Tucuruí . discount rate at which this turnover would occur would be lower were a pr accounting made of many of Tucuruí's emissions (construction, displaced deforestation, etc.). It should also be remembered that Tucuruí is better than the average dam.

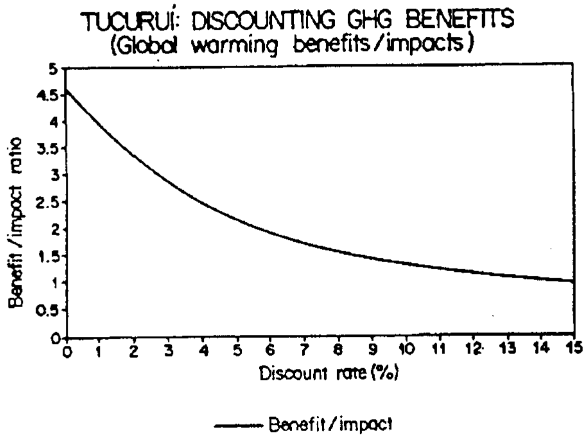

Figure 6. Tucuruí: discounting greenhouse gas benefits and impacts (global warming benefit/impact ratios).

Discounting would have a significant effect on the importance given to emissions from the construction phase of hydroelectric dams, such as those from the concrete, steel and transport of materials. Because these emissions occur before the dams are closed, the year of emission is negative and their impact will have to be inflated, rather than deflated, to standardize them to year zero. As compared to fossil fuels, the long lead time of hydroelectric dam construction, as well as the greater requirements for materials, will make this factor weigh against hydro.

5. *Conclusions*

The Tucuruí Dam produces significant emissions of greenhouse gases, although less would be produced by fossil fuels when considered over a 100-year time horizon. The relative attractiveness of hydroelectric versus thermoelectric generation, in terms of global warming impact, is highly sensitive to discount rate or other forms of weighting for time preference. The global warming impacts of Tucuruí can even exceed those of fossil fuel generation if assessed using discount rates common in financial analyses (a practice within the range of discussion, although not recommended by this author). Because the ratio of energy benefits to global warming impacts at Tucuruí is more favorable than with the average existing dam, or the average planned dam in Brazilian Amazonia, decisions regarding discounting of global warming impacts will be critical to the choices to be made among energy options in the region.

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Tabela 1.

TABLE 1: PARAMETERS FOR HYDROELECTRIC DAM EMISSION CALCULATIONS

Parameter	Value	Units	Source
Above-ground fraction	0.773		Fearnside, nd-b; see Fearnside, 1994
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
Above-water decay rate (0-4 yrs)	-0.1691	Fraction/yr	Assumed same as felled forest (Fearnside, 1996a)
Above-water decay rate (5-7 yrs)	-0.1841	Fraction/yr	Assumed same as felled forest (Fearnside, 1996a)
Above-water decay rate (8-10 yrs)	-0.0848	Fraction/yr	Assumed same as felled forest (Fearnside, 1996a)
Above-water decay rate (>10 yrs)	-0.0987	Fraction/yr	Assumed same as felled forest (Fearnside, 1996a)
Fraction of above-water decay via termites	0.0844	Fraction	Assumed same as felled forest (Martius et al., 1996)
Wood decay rate in surface water zone	-0.0139	Fraction/yr	Assumption: average lifetime = 50 years
Leaf decay rate in anoxic water zone	-0.0035	Fraction/yr	Assumption: average lifetime = 200 years
Wood decay rate in anoxic water zone	-0.0014	Fraction/yr	Assumption: average lifetime = 500 years
Below-ground decay rate in permanently flooded zone	-0.0014	Fraction/yr	Assumption: average lifetime = 500 years
Below-ground decay rate in seasonally flooded zone	-0.0139	Fraction/yr	Assumption: average lifetime = 50 years
Fraction of C released as methane in termite decay	0.0000		Calculated from measurement by Martius et al. (1993) for Nasutitermes macrocephalus (a várzea species)
Fraction of C released as methane in termite decay (high trace gas scenario)	0.0000		Calculated from measurement by Martius et al. (1993) for Nasutitermes macrocephalus (a várzea species)
Fraction of C released as methane in surface water zone decay	0		Assumption
Fraction of C released as methane in anoxic water zone decay	1		Assumption
Fraction of C released as methane in below-ground decay	1		Assumption

action of water covered by macrophytes	0.1		Assumption
Methane release from macrophyte beds	0.00	mg/m2/day	Fearnside, 1995: Table VIII
Methane release from open water	0.00	mg/m2/day	Fearnside, 1995: Table VIII
Carbon content of wood	0.00		Fearnside et al., 1993
Carbon content of leaves and fine litter	0.45		Assumption
Carbon content of vines and epiphytes	0.45		Assumption
Rate of wood fall from above-water zone	0.1155	Fraction/yr	Assumption: average lifetime = 6 years
Fraction of methane oxidized in water	0		Assumption
Leaf aerobic decay, first year	0.025	Fraction of original leaf biomass lost annually	Calculated from Brazil, ELETRONORTE, 1987: 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: 261
			Value divided by 10 (as a guess at the exaggeration in OXY-STRATIF)

Biomass of Components in Unlogged Original Forests

Average total biomass of forest	0	t/ha	Revilla Cardenas et al., 1982
Average water depth at minimum level	10	meters	Assumption
Initial biomass present: leaves	8.8	t/ha	From total biomass and Fearnside, 1995: Table IV.
Initial biomass present: fine litter	10.6	t/ha	From total biomass and Fearnside, 1995: Table IV.
tial biomass present: vines and epiphytes	22.5	t/ha	From total biomass and Fearnside, 1995: Table IV.
tial biomass present: wood above water	291.4	t/ha	From total biomass and Fearnside, 1995: Table IV.
tial biomass present: wood in surface zone	5.3	t/ha	From total biomass and Fearnside, 1995: Table IV.
tial biomass present: wood in anoxic zone	55.5	t/ha	From total biomass and Fearnside, 1995: Table IV.
Initial biomass present: below ground	121.9	t/ha	From total biomass and Fearnside, 1995: Table IV.