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COMMENT

Are hydroelectric dams in the Brazilian Amazon significant sources of 'greenhouse' gases?

Introduction

Possible implications of climate change have motivated a series of studies on the greenhouse gas (GHG) emissions from hydroelectric dams (Oud 1993; Rudd *et al.* 1993). Some of these studies have addressed the methodological issue of how adequately to compare the relative contributions of different gases emitted at different times to the greenhouse effect so as to help determine the global impact of different energy technologies (Rosa & Schaeffer 1994; 1995). Such is the case with methane (CH_4) and carbon dioxide (CO_2) emissions from bacterial decomposition of organic matter in hydroelectric dams, and CO_2 emissions from fossil-fuel use in thermal power plants.

In a recent paper Fearnside (1995) suggested that, per unit of electrical energy produced, the global warming impact of Amazonian hydroelectric dams is much higher than the impact of fossil-fuelled power plants. We seriously question his findings. A close examination of his work shows that the results are strongly dependent upon the generalization of a single low ratio of energy produced to flooded area (probably the lowest of all existing and planned dams in Brazil) to all possible future hydroelectric reservoirs in the Amazon region, when the known ratios spread over a range as wide as 0.0003 TWh yr^{-1} km^{-2} for the Balbina dam (the ratio used by Fearnside himself) to 0.0438 TWh yr^{-1} km^{-2} for the planned Belo Monte hydroelectric dam (Rosa & Schaeffer 1995), i.e. a 146:1 variation. Although we do not want to contest the results for the Balbina dam based on the assumptions he has used for that dam in particular, we believe that the author's conclusions for hydroelectric reservoirs in the Amazon as a whole are based on the generalization of single-point data that are not representative of the region, and are therefore misleading. In addition, Fearnside (1995) is also confusing the issue of quantitatively comparing greenhouse-gas emissions from different modes of energy production with the question of determining the warming effects of those emissions over a certain time horizon. The latter analysis requires an evaluation of the cumulative greenhouse effect of gas emissions from hydroelectric reservoirs and fossil-fuelled power plants alike, by considering both the variation of their emissions over time as well as the residence times of the gases in the atmosphere. The purpose of this comment is to elaborate these issues further so as to help clarify the potential contribution of hydroelectric reservoirs in the Brazilian Amazon region to the greenhouse effect.

Calculation of budgets

The total carbon present in the flooded vegetation and soil of a hydroelectric reservoir can be decomposed aerobically and/or anaerobically, producing either CO_2 or CH_4, or both. Fearnside (1995), based on data from specific measurements, has assumed that CO_2 emissions would prevail, although some minor contributions of CH_4 have also been considered, and converted to CO_2-equivalent carbon using a Global Warming Potential (GWP) for direct effect only, and over a 100-year time-horizon, equal to 11 on a kg-per-kg basis.

We have even been cited in his paper as if we had used this same GWP in a similar study (Rosa & Schaeffer 1994). On the contrary, instead of using the current definition of GWP we have in fact shown that the current GWP index is inappropriate for dealing with GHG emissions from hydroelectric reservoirs when comparing them with emissions from fossil-fuelled power plants. The definition of GWP by Lashof and Ahuja (1990) is based on the ratio of the instantaneous radiative forcing of a pulse emission of a particular greenhouse gas and that of an equal and simultaneous emission of a reference gas (chosen to be CO_2) integrated up to an arbitrarily determined time-horizon. However, it is obvious that the pattern of GHG emissions from hydroelectric dams is substantially different from the pattern of emissions from fossil-fuelled power plants. Therefore, in order to compare the cumulative heating effects of emitted amounts of

CH_4 and CO_2 with each other, three factors must be considered: (1) the instantaneous radiative forcing due to a unit increase in the concentration of the gases, (2) the decay time functions of the gases in the atmosphere and, last but not least, (3) the emission patterns of the gases. So, even to compare CO_2 emissions from hydroelectric reservoirs with CO_2 emissions from fossil-fuelled power plants, as is the case in the simulations made by Fearnside (1995, Fig. 4), we must consider that reservoir emissions are strongly concentrated within a few years after filling. In order to contrast those emissions with the constant and continuous emissions from equivalent fossil-fuelled power plants, it is not rigorous enough simply to compare quantitatively the amounts of gases emitted in each case, since the real warming effects can only be determined after an integration over time, taking into account the temporal pattern of the emissions.

For the sake of simplicity, Fearnside (1995) has created a model for estimating emissions from hydroelectric dams with several other assumptions as a background; some of these are quite reasonable and others have a high degree of uncertainty. Focusing in particular on the ultimate contribution of hydroelectric flooding to atmospheric carbon, and dismissing the impact of this flooding on the annual balance of emissions, Fearnside (1995) has assessed the quantities, types and vertical distribution of biomass in areas flooded by Amazon reservoirs, paying special attention to the portion of the trees projecting out of the water. It is assumed that emergent tree materials would decay through processes similar to those affecting trees felled in clearings for agriculture and ranching. Fearnside (1995) has also assumed that part of that biomass would be ingested by termites, emitting small amounts of CH_4, and that part would decompose in the aerobic environment above the water level producing CO_2 only.

Fearnside (1995, Table XI) has presented figures comparing emissions from two hydroelectric dams (Balbina and Tucurui) in the Brazilian Amazon for a single year (1990) with emissions from fossil-fuelled power plants. However, on more than one occasion, Fearnside (1995, Figs. 4, 5 & 6) has shown that GHG emissions from hydroelectric reservoirs are concentrated in time, with most of the emissions taking place only a few years after closing. So, what is the meaning of comparing emissions from dams with emissions from fossil-fuelled power plants in a single year?

In the case of Tucuruí, for example, the emissions estimated for 1990 are 0.16 MtC TWh^{-1}, while the values for natural gas- and coal-fuelled power plants are 0.11 and 0.27 MtC TWh^{-1}, respectively (the figures have been mistakenly exchanged in Fearnside 1995). Could we conclude that Tucurui emissions (not to mention their cumulative heating effects) are higher than those of an equivalent natural gas-fuelled power plant in the long term just because emissions from the dam have been calculated as being higher for a single year, a few years after closing?

The above- and surface-water wood (the majority of emissions are supposed to come from these regions) present in the Tucuruí reservoir in 1990 at minimum operating water-level would have amounted to 6.41 MtC, and the total figure for CO_2-equivalent carbon emissions (100 years, zero discount direct effects) from the entire reservoir for that particular year would have been 2.85 MtC according to Fearnside (1995, Tables VII & IX). So, for the emission rate calculated by Fearnside (1995) for 1990, the lifetime of the flooded biomass would be some 2.25 years. In that case, after less than three years there would be no more above-water biomass left in the reservoir if CO_2 emissions were constant at the 1990 level. It is clear, however, that the emissinn would not remain that high; it would decrease following exponential functions with time constants similar to those assumed by Fearnside (1995, Table VI).

The total carbon initially present in the zone of the Tucuruí dam that will decay within the first 100 years after clnsing is approximately 35 MtC, while the tutal carboo emission from an equivalent natoral gas-fuelled power plant generating 18.03 TWh yr^{-1} over 100 years is some 198 MtC, using the same 0.11 MtC TWh^{-1} factor (Fearnside 1995). The low availability of natural gas in Brazil, however, even including possible imports from Bolivia, will probably limit its utilization for power generation. Other competing uses, such as for residential, transportation and industrial purposes, will probably take most of the natural gas made available in the future. Therefore, in the hypothesis of fossil-fuelled power generation as a substitute for hydroelectricity in Brazil, coal-fuelled power plants will probably take the larger share. In the case of a Tucuruí-equivalent coal-fuelled power plant, total carbon emissions would reach some 486 MtC, or 14 times more than the 35 MtC estimated for Tucuruí.

An alternative approach to calculating emissions from reservoirs

In a previous paper (Rosa *et al.* 1994) cited by Fearnside (1995), two of us have also studied greenhouse-gas emissions from hydroelectric reservoirs. We have considered both CH_4 and CO_2 emissions taking into account the instantaneous radiative forcing due to a unit increase in the concentration of gases, different emissions patterns, different decay times of the gases in the atmosphere, different biomass densities and types in the flooded area, as well as different shares of CH_4 and CO_2 in total emissiuns. But, because Fearnside (1995) is more concerned with CO_2 emissions from the above-water biomass, for the sake of simplicity we restrict ourselves here to comparing the warming effects of CO_2 emissions from hydroelectric reservoirs with the warming effects of CO_2 emissions from fossil-fuelled power plants. This is possible if we determine the integrated radiative forcing of all emissions involved, as fnllows (Rosa & Schaeffer 1994; 1995):

$$E_{H2} = \frac{\beta C}{\lambda_2} - \frac{\gamma \beta C}{\lambda_2 - \gamma}\left(\frac{e^{-\gamma T}}{\gamma} - \frac{e^{-\lambda_2 T}}{\lambda_2}\right) \tag{1}$$

$$E_{F2} = \frac{n_2 T}{\lambda_2}\left(1 - \frac{1 - e^{-\lambda_2 T}}{T\lambda_2}\right) \tag{2}$$

where E_{H2} is the integrated effect of CO_2 emissions from a hydroelectric reservoir remaining in the atmosphere at time T; E_{F2} is the integrated effect of CO_2 emissions from a fossil-fuelled power plant remaining in the atmosphere at time T; C is the total mass of degradable carbon in the vegetation and soil that would decay in a reservoir within time T; β is the fraction of C that would be released as CO_2; n_2 is the mass of carbon that is emitted annually as CO_2 from a fossil-fuelled power plant; γ is the time cnnstant for the assumed exponential decomposition rate in the reservoir; λ_2 is the time constant for CO_2 in the atmosphere; and T is the time-horizon considered.

Fearnside (1995) has simply accounted for total carbon masses emitted from both hydroelectric dams and fossil-fuelled-equivalent power plants. With the above formulatinn the carbon masses are:

$$C_{H2} = \beta C(1 - e^{-\gamma T}) \tag{3}$$

$$C_{F2} = n_2 T \tag{4}$$

Through direct inspection it is straightforward tn verify that, in general,

$$\frac{E_{H2}}{E_{F2}} > \frac{C_{H2}}{C_{F2}} \tag{5}$$

and, in the usual situation in which $\gamma >> \lambda_2$ and $\gamma T >> 1$,

$$\frac{E_{H2}}{E_{F2}} = \frac{1 - e^{-\lambda_2 T}}{1 - \left(\frac{1 - e^{-\lambda_2 T}}{T\lambda_2}\right)} \frac{C_{H2}}{C_{F2}} \tag{6}$$

It is clear that, once $T \rightarrow \infty$, we also have

$$\frac{E_{H2}}{E_{F2}} = \frac{C_{H2}}{C_{F2}} \tag{7}$$

Fearnside (1995) assumed a linear superposition of decay functions for the biomass decompositinn that, in our formulation, can be represented as follows:

$$C_{F2} = \sum_i \beta_i C(1 - e^{-\gamma_i T}) \tag{8}$$

although we can also generalize our cumulative effect as a linear superposition.

In previous works we have also studied greenhouse-gas emissions from hydroelectric dams in the Brazilian Amazon, three of which have also been investigated by Fearnside (1995), but our procedure has been more rigorous regarding a reservoir's contribution to global warming. When we limit our time-horizon of concern to some arbitrary time, say $T = 100$ years, for instance, we are not computing the warming effects of the CO_2 remaining in the atmosphere due to emissions from a fossil-fuelled power plant that have occurred some time before or after that. This is because the lifetime of CO_2 in the atmosphere is some 120 years, and as such most of the heating effects of the CO_2 emitted close to $T = 100$ years have almost no impact in the calculations. Even so, our results, even incorporating the CH_4 emissions not considered by Fearnside (1995), do not agree with those of his study for the case of Tucurui, although we are qualitatively in agreement with his findings for both Samuel and Balbina dams.

Our results have shown that, though the cumulative heating effects of emissions from hydroelectric reservoirs are far from negligible, for the cases of Belo Monte, Samuel and Tucuruí, where energy densities are much higher than that of Balbina, hydroelectricity contributes less to the greenhouse effect than equivalent fossil-fuelled power plants (Rosa *et al.* 1994; Rosa & Schaeffer 1995).

We have calculated carbon emission effects for three hypothetical hydroelectric power plants with energy densities similar to Samuel (A), Tucuruí (B) and Belo Monte (C) dams. The avoided emission, defined as the difference between the fossil-fuelled power plant emission and that from a hydroelectric reservoir, is quite sensitive to the energy density of the dam. Balbina's energy density amounts to 0.0003 TWh yr^{-1} km^{-2} (Fearnside 1995), while Tucuruí's is 0.0071 TWh yr^{-1} km^{-2} and Belo Monte's is 0.0438 TWh yr^{-1} km^{-2} (Rosa *et al.* 1994; Rosa & Schaeffer 1995); this is a 146-fold range. We have assumed that 30% of the above-ground biomass in the reservoirs decays exponentially over time to CH_4 with a time constant of seven years. The results for $T = 100$ years can be seen in Table 1. Only hydro type A has a warming effect higher than that of an equivalent combined-cycle natural gas-fuelled power plant, but it is not higher than that of a coal-fuelled power plant.

Table 1 Total integrated radiative forcing from hydroelectric and fossil-fuelled power plants. Adapted from Rosa and Schaeffer (1995).

Power plant	*Energy density (TWh yr^{-1} km^{-2})*	*Integrated radiative forcing*[a,b] *(equiv. MtC yr^{-1} TWh^{-1})*
Hydro A[c]	0.0017	6.27
Hydro B[d]	0.0071	1.50
Hydro C[e]	0.0438	0.25
Fossil-fuelled	–	4.45[f]–10.23[g]

[a] Although cumulative forcing is normally expressed in W m^{-2} yr^{-1}, we have decided to use MtC yr^{-1} equivalent units as a basis for comparison.
[b] Biomass value of 361.5 t ha^{-1} dry weight (Setzer & Pereira 1991), with a carbon stock of 45% of the dry biomass, 30% of which assumed to decompose anaerobically.
[c] Hydroelectric power plant similar to Samuel in terms of energy density.
[d] Hydroelectric power plant similar to Tucuruí in terms of energy density.
[e] Hydroelectric power plant similar to the proposed Belo Monte hydroelectric power plant in terms of energy density.
[f] Combined-cycle natural gas-fired power station with an assumed 45% thermal efficiency and burning gas with CO_2 emissions of 13.7 kgC 10^{-9} J of fuel.
[g] Coal-fired power station with an assumed 35% thermal efficiency and burning coal with CO_2 emissions of 25.2 kgC 10^{-9} J of fuel.

Final remarks

The question we have to pose is: Why do Fearnside's (1995) conclusions differ so much from ours? Different parameters used, such as different biomass densities for the flooded areas, are certainly not enough to explain the quantitative discrepancies. The fact that we have assumed that CH_4 emissions would prevail over CO_2 emissions while Fearnside (1995) has assumed that CO_2 emissions would dominate, does not explain the differences either, since the GWP of CH_4 is much higher than that of CO_2 and our method accentuates this difference. The answer seems to lie in methodological grounds.

One possible clue to help explain part of the differences is that while Fearnside (1995) has concentrated his analysis on quantitatively estimating greenhouse-gas emissions for both hydroelectric reservoirs and fossil-fuelled power plants, we have focused on determining the cumulative heating effects of those emissions over time; the results are quite different. Fearnside (1995) has not distinguished between emissions and the warming impacts of those emissions. The picture for hydroelectric dams improves when we do not limit the analysis to mass balances of carbon but compare the real cumulative heating effects of those emissions, which should be the sole purpose of this kind of study.

Though we need to recognize that hydroelectricity may have serious environmental impacts, the evidence we have gathered so far seems to indicate that hydroelectric dams in the Brazilian Amazon are a realistic mitigation option for global climate change (even taking into consideration recent measurements of CO_2 that have indicated an average carbon absorbed by tropical rain forests in Amazonia over the year as 8.5 ± 2 moles $m^{-2} yr^{-1}$ [Grace *et al.* 1995], or some 0.32 ± 0.08 MtC yr^{-1} in the case of the Balbina reservoir that have not been absorbed any more and some 0.23 ± 0.05 MtC yr^{-1} in the case of the Tucuruí reservoir). In summary, although the generation of hydropower is said to have avoided worldwide some 9% of the CO_2 from fossil fuel combustion in 1994 based on the underlying assumption that the generation is not associated with GHG emissions (Vate 1996), we confirm that hydroelectric reservoirs may be significant sources of greenhouse gases and the cumulative heating effects of their emissions may be far from negligible. But our studies for the Brazilian Amazon region have indicated that hydroelectricity in general contributes less to enhance the greenhouse effect over a loog-time horizon than fossil-fuelled electricity generation. Besides, it is important to mention, recent studies have eveo indicated that man-made lakes may be the single largest (and negative) contribution to sea level (Chao 1994; Rodenburg 1994; Sahagian *et al.* 1994). This is because a possible rise in sea level would have been even larger if large quantities of water had not been stored in hydroelectric reservoirs. But this positive contribution of reservoirs still needs to be better evaluated in the case of hydroelectric dams in the Brazilian Amazon.

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