

# Fizzy Science

Loosening  
the Hydro Industry's  
Grip on Reservoir  
Greenhouse  
Gas Emissions  
Research



**International Rivers Network**

[www.irn.org](http://www.irn.org)

## **About IRN**

International Rivers Network protects rivers and defends the rights of communities that depend on them. IRN opposes destructive dams and the development model they advance, and encourages better ways of meeting people's needs for water, energy and protection from damaging floods.

© International Rivers Network  
November 2006

International Rivers Network  
1847 Berkeley Way  
Berkeley, CA 94703, USA  
Tel: +1 510.848.1155  
Fax: +1 510.848.1008  
irn@irn.org  
www.irn.org

Front cover photos: Tucuruí dam by Eneida Castro and Hicham Daoudi;  
Petit Saut reservoir by Jacky Brunetaud.  
Back cover photo: Tucuruí reservoir by Glenn Switkes.

Written by: Patrick McCully  
Editing by: Lori Pottinger  
Production by: Elizabeth Brink  
Design by: Jeanette Madden  
Printing by: Hunza Graphics  
Printed on 100% recycled paper.

## INTRODUCTION

The pages of a respected climate change journal are not a place one would expect to find a bad-tempered exchange over the merits of iconic soft drinks. Yet such a disagreement – over the rates at which Coca-Cola and Brazilian *guaraná* lose their fizz – was recently covered in the normally decorous pages of *Climatic Change*. While the immediate topic seems inconsequential to say the least, the larger context is of major importance – do tropical hydropower reservoirs cause greenhouse gas emissions to match those from fossil fuel plants?

Reservoir emissions research is highly politically charged and largely unknown by those outside the immediate field. Measurements have been made at only a tiny percentage of the world's half million or so freshwater reservoirs.<sup>1</sup> Yet despite the preliminary nature of the science and its many complexities and uncertainties, available evidence strongly suggests that reservoirs are a significant global source of greenhouse gases, in particular methane.<sup>2</sup>

There are a number of reasons for the low awareness of reservoir emissions even among policy makers and scientists working on climate-related issues: the science is still relatively young, comparatively little has been published on it in peer-reviewed journals, and numerous uncertainties about net emissions levels remain to be resolved.

Danny Cullenward and David G. Victor of Stanford University wrote an editorial in *Climatic Change* in March 2006 in response to the Coke vs *guaraná* dispute. They note that most of the published work on reservoir emissions “comes directly from researchers connected to hydroelectricity companies, such as Eletrobrás or Hydro-Québec.” The Stanford analysts propose that a mechanism is needed to remove “any taint of interest” from reservoir emissions research. They believe that the best way to do this would be through a Special Report of the Intergovernmental Panel on Climate Change (IPCC). Cullenward and Victor note that the IPCC “is the only forum that could sustain the scientific integrity and transparency needed to synthesize the full international debate over emissions from hydroelectricity, as well as to make the information from such assessments available to climate policy makers in governments and international organizations.”<sup>3</sup>

The IPCC recognized in its 2006 guidelines on greenhouse gas inventories that reservoirs are a source of emissions, but also that more research is needed to be able to accurately quantify the extent of these emissions, especially of methane. It is a logical next step for the IPCC to take the lead in carrying out a comprehensive and independent review of research into reservoir emissions to inform their future guidance on measuring GHG fluxes.

Reservoir emissions were also recognized as an issue of concern in early 2006 by the governing board of the Clean Development Mechanism, the Kyoto Protocol's main carbon trading system. The CDM's Executive Board ruled that projects with large reservoirs relative to their generation capacity will not for the time being be allowed to sell carbon credits. The board's decision leaves open the possibility that they could in the future approve large reservoirs for carbon credits without adequately allowing for their emissions. This loophole should be closed and hydro projects with large reservoirs made ineligible for CDM credits.

The Executive Board distinguishes between hydro projects that may have high, medium or low emissions using largely arbitrary criteria based upon their “power density” (power generation capacity divided by

area flooded). An IPCC Special Report could provide a scientific basis upon which the CDM could base its methodology for accounting for reservoir emissions.

## THE CARBONATED DRINK SKIRMISH AND THE RESERVOIR EMISSION WARS

The Coke versus *guaraná* skirmish was inadvertently started by ecologist Philip Fearnside of the National Institute for Research in the Amazon (INPA), in Manaus, Brazil. Fearnside, the world's second most-highly cited scientist on global warming in the decade up to 2006,<sup>4</sup> is originally from the US but has been based in Brazil for the past 30 years. Writing in the September 2004 issue of *Climatic Change*, Fearnside used a comparison with the fizzing of a newly opened bottle of Coke to explain the massive surge of methane emissions that can occur by “degassing” when water is discharged under pressure at hydropower dams. According to Fearnside's calculations, degassing emissions from several large hydro dams in the Brazilian Amazon make these plants much larger contributors to global warming than fossil-fuel alternatives.

Fearnside has been in a long-running scientific feud on the scale of Brazilian hydropower's global warming impact with a team from the graduate engineering department (known as COPPE) at the Federal University of Rio de Janeiro. This team is led by Luis Pinguelli Rosa, who served from 2003 to 2005 as head of Brazil's Eletrobrás, one of the world's largest hydropower producers. Pinguelli Rosa and his colleagues also published an article in the September 2004 issue of *Climatic Change* which implied that Fearnside and others who argue that dams can have high greenhouse gas emissions are being seduced by the “lures of the thermo-power and nuclear-power lobbies.”<sup>5</sup>

Pinguelli Rosa *et al.* published another *Climatic Change* article in 2005 responding to Fearnside's Coke analogy with the criticism that not all of the CO<sub>2</sub> in the bottle escapes immediately after it is opened. Bubbles, Pinguelli Rosa *et al.* point out, can be seen rising from a Coke bottle for “many minutes” after it is opened. Fearnside, they claim “seems unaware of empirical observation, clinging to his idealized convictions, whose theoretical grounds are certainly open to discussion.” They also more generally (if somewhat bizarrely) say that the use of the US drink is “highly symbolic of [Fearnside's] way of thinking.”

The COPPE researchers put forward the popular Brazilian carbonated drink *guaraná* as a better tool to understand hydropower degassing. They note that *guaraná* is transparent while Coke is dark, so that its bubbles can be more easily seen, and people in Brazil “often sit around a table to chat as they drink it, with the bottles open and the glasses full for half an hour or more, without completely losing the bubbles. Instead of fast food, the Brazilian custom is a leisurely drink.” More to the point, they say that the gas “does not escape in a few seconds from either the soda-pop bottle or the hydroelectric dam tailrace, as quite groundlessly affirmed by Fearnside.” The COPPE team state that this supposed misconception of Fearnside's, together with “several scientific errors,” explain why his calculation of emissions from Tucuruí, one of the largest reservoirs in the tropics, are several times higher than their calculation (see Table 1 and Figures 1 and 2).<sup>6</sup>

Fearnside responded to the COPPE team with another article in *Climatic Change*, accusing Pinguelli Rosa and his co-workers of having “effectively made a career of trying to prove me wrong” since his first estimate of high emissions from Amazonian dams in 1995. Fearnside strongly defends the assumptions and conclusions of his previous paper and states that it makes little difference whether one assumes that dam degassing happens in 30 seconds or “the half hour they refer to for the last bubbles to emerge from a leisurely consumed bottle of Brazil's politically correct soft drink – *guaraná*.” In either case, the high

concentration of methane in the discharged water is emitted before there is time for bacteria in the river to degrade it to carbon dioxide, a much less potent greenhouse gas. Fearnside notes that “the longer this debate goes on and the more information that becomes available, the greater the [climate] impacts [of tropical hydropower dams] are found to be.”<sup>7</sup>

This spat over soft-drink culture is just the latest skirmish in the reservoir emission wars. These began in the mid-1990s when scientists working in the Canadian province of Manitoba published the first papers hypothesizing that reservoirs might be significant emitters of GHGs.<sup>8</sup> Soon after, Pinguelli Rosa and Fearnside published their initial findings on Brazilian reservoir emissions.<sup>9</sup>

The initial response from much of the hydropower industry to assertions that hydropower reservoirs were a source of GHGs on the scale of fossil fuel emissions per unit of generation was sputtering disbelief. A spokeswoman for the US National Hydropower Association responded to an IRN press release on reservoir emissions in 1995 with the statement that “It’s baloney and it’s much overblown...Methane is produced quite substantially in the rain forest and no one suggests cutting down the rain forest.”

There are still those in the hydropower industry and elsewhere who continue to claim that reservoirs have no, or only negligible, climate impact, but most knowledgeable hydropower advocates now admit that, at least for some tropical reservoirs, GHG emissions may be substantial.

The assertions by Fearnside and the Manitoba scientists that hydropower could be a significant GHG source was of great concern to the hydropower industry, which was then beginning to market itself as “climate-friendly” and “zero-carbon.” The huge utility Hydro-Québec soon started to finance studies into reservoir emissions. In the second half of the 1990s, Hydro-Québec began long-term collaborations on reservoir GHG studies with COPPE researchers financed by the Brazilian government and hydropower utilities.<sup>10</sup>

Since 2000 the literature on hydropower emissions has grown relatively rapidly. It continues to be dominated by scientists in Brazil and Canada, with important contributions from scientists supported by Electricité de France who have published several papers on the Petit Saut reservoir in French Guyana. Two books of essays on reservoir emissions were published in 2005, one published by COPPE and the Brazilian utility Eletrobrás, the other a 730-page volume (from science publisher Springer) edited by Alain Tremblay and Louis Varfalvy of Hydro-Québec and two Hydro-Québec-sponsored academics. Neither volume contains contributions from Fearnside, nor from Éric Duchemin, a leading Québécois researcher on reservoir emissions who has remained independent of Hydro-Québec.<sup>11</sup> The International Hydropower Association, in which Hydro-Québec plays an influential role, has published several fact sheets and articles based on the utility’s reservoir emissions research and analysis. A booklet produced by IRN in 2002 is probably the only non-industry funded publication devoted to reservoir emissions.<sup>12</sup>

The Hydro-Québec researchers take a particularly fundamentalist line on the climate benefits of hydropower and often ignore not only Fearnside’s research, but even that of their counterparts at COPPE. The manager of Hydro-Québec’s Greenhouse Gas Program, Alain Tremblay, for example, repeatedly claims that hydropower plants as a whole “generate 35-70 times less” GHGs per unit of power produced than fossil fuel plants.<sup>13</sup> Such a conclusion ignores the science on tropical reservoirs. In addition to sponsoring researchers, Hydro-Québec’s efforts to control the terms of the debate have included cutting the funding of a team of Québécois reservoir emissions researchers, and trying to persuade an academic journal not to publish a peer-reviewed paper on reservoir emissions written by some of these researchers.<sup>14</sup>



**TABLE 1. GREENHOUSE GAS EMISSIONS FROM HYDROPOWER PLANTS**

| Hydro plant                                 | Power density (W/m <sup>2</sup> ) | Installed capacity (MW) | Flooded area (km <sup>2</sup> ) | CO <sub>2</sub> reservoir surface (Mt gas/yr) | CH <sub>4</sub> reservoir surface (Mt gas/yr) | CH <sub>4</sub> degassing (Mt gas/yr) | Total emissions (Mt CO <sub>2</sub> -eq/yr) | Electricity generation (GWh/yr) | Reservoir age (years) <sup>§</sup> | Emissions per kWh (gCO <sub>2</sub> -eq/kWh) |
|---|-----------------------------------|-------------------------|---------------------------------|---|---|---------------------------------------|---|---------------------------------|------------------------------------|--|
| Boreal gross (Canada)                       |                                   |                         |                                 |   |   |                                       |   |                                 |                                    |  |
| Sainte-Marguerite                           | 10.38                             | 882                     | 85                              | 0.02  | 0.000   |                                       | 0.02  | 2,770                           | N/A                                | 8  |
| Churchill/Nelson                            | 2.80                              | 3,925                   | 1,400                           | 0.22  | 0.003   |                                       | 0.28  | 14,000                          | N/A                                | 20   |
| Manic Complex                               | 1.91                              | 5,044                   | 2,645                           | 0.64  | 0.008   |                                       | 0.80  | 20,000                          | N/A                                | 40   |
| La Grande Complex                           | 1.20                              | 15,552                  | 13,000                          | 3.28  | 0.039   |                                       | 4.10  | 82,000                          | N/A                                | 50   |
| Churchill Falls                             | 0.81                              | 5,428                   | 6,705                           | 1.67  | 0.020   |                                       | 2.09  | 35,000                          | N/A                                | 60   |
| Average                                     | 3.42                              | 6,166                   | 4,767                           | 1.17  | 0.014   |                                       | 1.46  | 30,754                          | N/A                                | 36   |
| Tropical "reservoir net"* (Brazil)          |                                   |                         |                                 |   |   |                                       |   |                                 |                                    |  |
| Tucuruí                                     | 1.74                              | 4,240                   | 2,430                           | 9.34 <sup>#</sup>                             | 0.094   | 0.970                                 | 31.56                                       | 18,030                          | 6 (1990)                           | 1,751  |
| Curuá-Una                                   | .56                               | 40                      | 72                              | 0.04 <sup>#</sup>                             | 0.001   | 0.022                                 | 0.51  | 190                             | 13 (1990)                          | 2,704  |
| Samuel                                      | 0.40                              | 216                     | 540                             | 0.22 <sup>#</sup>                             | 0.010   | 0.030                                 | 1.06  | 530                             | 12 (2000)                          | 2,008  |
| Average                                     | 0.90                              | 1,499                   | 1,014                           | 3.20 <sup>#</sup>                             | 0.035   | 0.341                                 | 11.05                                       | 6,250                           |                                    | 2,154  |
| Balbina                                     | 0.08                              | 250                     | 3,150                           | 23.60   | 0.036   | 0.034                                 | 28.44                                       | 970                             | 3 (1990)                           | 29,322                                       |
| Petit Saut (French Guyana)                  | 0.32                              | 115                     | 365                             | 0.24  | 0.012   | 0.023                                 | 1.21  | 470                             | 20 year avg                        | 2,577  |
| Tropical gross excluding degassing (Brazil) |                                   |                         |                                 |   |   |                                       |   |                                 |                                    |  |
| Xingó                                       | 50.00                             | 3,000                   | 60                              | 0.13  | 0.001   |                                       | 0.15  | 13,140                          | 4-5                                | 12   |
| Segredo                                     | 15.37                             | 1,260                   | 82                              | 0.08  | 0.0003  |                                       | 0.09  | 5,519                           | 6-7                                | 16   |
| Itaipú                                      | 8.13                              | 12,600                  | 1,549                           | 0.10  | 0.012   |                                       | 0.34  | 55,188                          | 16-17                              | 6  |
| Miranda                                     | 7.65                              | 390                     | 51                              | 0.08  | 0.003   |                                       | 0.14  | 1,708                           | 2-3                                | 83   |
| Tucuruí                                     | 1.74                              | 4,240                   | 2,430                           | 7.52  | 0.097   |                                       | 9.55  | 18,571                          | 14-15                              | 514  |
| Serra da Mesa                               | 0.71                              | 1,275                   | 1,784                           | 2.59  | 0.033   |                                       | 3.28  | 5,585                           | 3-4                                | 588  |
| Barra Bonita                                | 0.45                              | 141                     | 312                             | 0.45  | 0.002   |                                       | 0.50  | 618                             | 36-37                              | 816  |
| Samuel                                      | 0.39                              | 216                     | 559                             | 1.52  | 0.021   |                                       | 1.97  | 946                             | 10-11                              | 2,077  |
| Três Marias                                 | 0.38                              | 396                     | 1,040                           | 0.42  | 0.075   |                                       | 1.99  | 1,734                           | 35-36                              | 1,147  |
| Average                                     | 9.43                              | 2,613                   | 874                             | 1.43  | 0.027   |                                       | 2.00  | 11,445                          | 14-15                              | 584  |

### Notes for Table 1

Blank entries = no data.

\* "reservoir net" includes CH<sub>4</sub> surface emissions, CO<sub>2</sub> from above-water decay of flooded biomass, and degassing emissions from turbines and spillways, minus pre-reservoir sources and sinks. It does not include CO<sub>2</sub> surface emissions (a proportion of these emissions will be produced by the decay of biomass in the reservoir which had when living consumed atmospheric carbon through photosynthesis in the reservoir). 99% of net CO<sub>2</sub> emissions for these projects are from above-water decay of flooded biomass.

§ Emissions from boreal hydros are calculated from averages across various reservoirs so "reservoir age" is not relevant for these plants. Balbina degassing emissions are from 2004 (17 years after filling). "Tropical gross excluding degassing" emissions are the average of measurements from two years (1998 and 1999). Petit Saut emissions are an average based on measurements and extrapolations for the 20 years after reservoir filling in 1994.

# CO<sub>2</sub> emissions from decay of above-water biomass.

Emissions data given in this table are based on available measurements and calculations for reservoirs for specific years. Emissions for specific reservoirs, and power generation, will vary widely between years. A full life-cycle assessment would include emissions due to construction, access roads, resettlement, decommissioning etc. CH<sub>4</sub> converted to CO<sub>2</sub>eq with GWP of 21. Generation figures for boreal reservoirs are estimates based on a 60% load factor. Generation figures for tropical net reservoirs are actuals. Generation figures for tropical gross reservoirs are estimates based on 50% load factor.

#### Sources:

*Boreal - Duchemin (2002).*

*Tropical "reservoir net" - Fearnside (2002) (2004b) (2005a) (2005b).*

*Tropical gross (including degassing) - Delmas et al. (2005). Generation figure from Ministère de l'Économie (2002).*

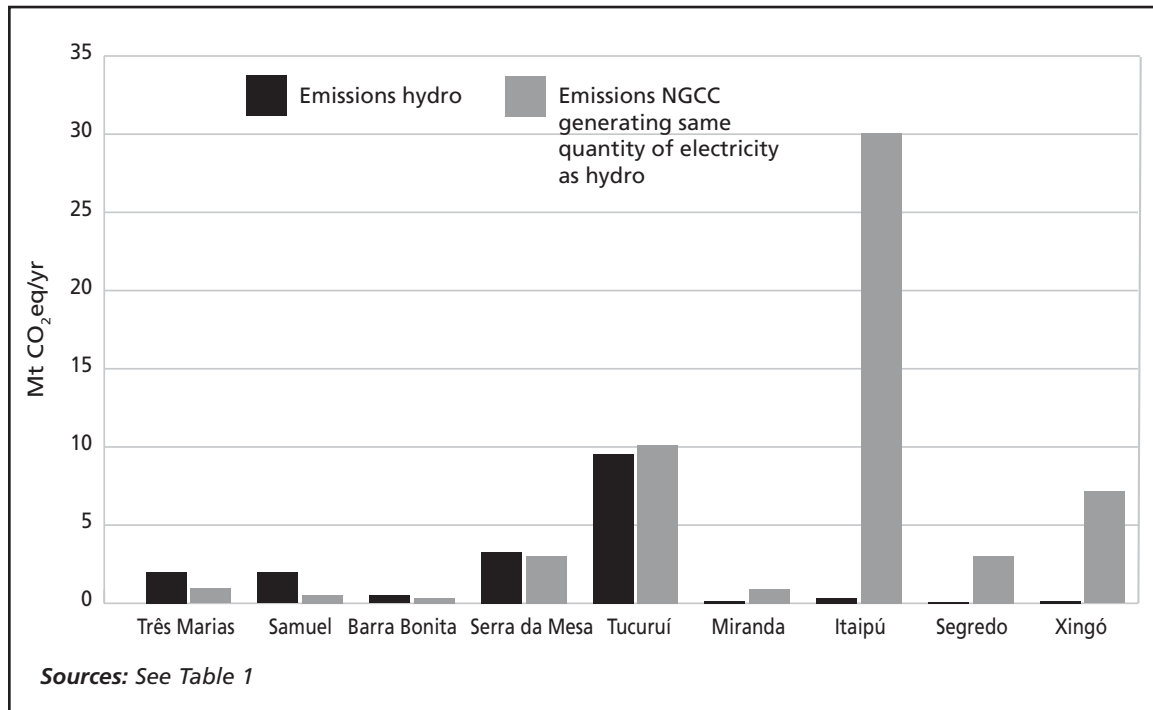
*Tropical gross (excluding degassing) - Santos et al. (2006).*

The main trend in reservoir emission science has been toward increasing recognition of the complexity of the pathways through which emissions are produced and released. Early work on the subject assumed that all emissions were fueled only by the biomass flooded when the reservoir was first filled, so that once this biomass had decomposed the emissions would stop. It is now understood that while there is a high initial pulse of emissions after reservoir filling, the emissions will continue to be fueled by carbon entering the reservoir throughout its lifetime. It was also believed that GHGs were emitted only at the reservoir surface, but it is now accepted that degassing at the dam can also be a source (although the actual scale of degassing emissions is hotly contested).

### STATE OF THE SCIENCE: A BASELINE OF AGREEMENT

Greenhouse gas emissions have now been measured at more than a hundred reservoirs, mostly in North America and Brazil.<sup>15</sup> Despite the many methodological and analytical disagreements between independent researchers and those linked to the hydro industry, there are many points on which there is no serious dispute.<sup>16</sup> These include:

**FIGURE 1. GROSS TROPICAL HYDRO EMISSIONS (EXCLUDING DEGASSING) COMPARED TO NATURAL GAS COMBINED CYCLE GENERATION**



- All reservoirs can be presumed to produce methane (CH<sub>4</sub>) and CO<sub>2</sub>. Reservoirs are also sources of the potent greenhouse gas nitrous oxide (N<sub>2</sub>O).<sup>17</sup> A small number of reservoirs in boreal and temperate zones have been found to be sinks for CO<sub>2</sub> and N<sub>2</sub>O.<sup>18</sup> (See Table 2)

- The gases are released via diffusion across the water surface and in bubbles that rise from the reservoir bottom. There can also be significant emissions, especially at dams in the tropics, from the degassing of water released through turbines and spillways. When water from below the surface of the reservoir is discharged at the dam, the pressure acting upon it suddenly drops and – according to the chemical principle of Henry’s Law – it is able to hold less dissolved gas. Degassing emissions are also due to the greater air/water interface created when water is pulverized at the bottom of a spillway or, as at Petit Saut, by a weir immediately downstream of the dam built to aerate the oxygen-depleted reservoir water and prevent it wiping out aquatic life downstream.<sup>19</sup>

- The major component of the warming impact of boreal reservoirs is diffusive CO<sub>2</sub>; the major component of the warming impact from the *surfaces* of tropical reservoirs is methane bubbles. For at least some tropical reservoirs the majority of their warming impact is due to methane degassing (see Table 1).

- The gases are formed by the decomposition in the reservoir of dissolved and particulate organic carbon. The main sources of this carbon – the “fuel” for the reservoir emissions – are the vegetation and soils flooded when the reservoir is first filled, the organic matter washed into the reservoir from upstream (which may be from natural or farmed ecosystems, or sewage from cities), the plankton and aquatic plants which grow and die in the reservoir, and the vegetation that grows on the “drawdown” land temporarily exposed during low reservoir periods. Reservoirs absorb atmospheric CO<sub>2</sub> due to photosynthesis by plank-



ton and aquatic plants; this uptake can occasionally exceed CO<sub>2</sub> emissions.<sup>20</sup> (See Figure 3 for a graphic representation of the main factors influencing emission levels.)

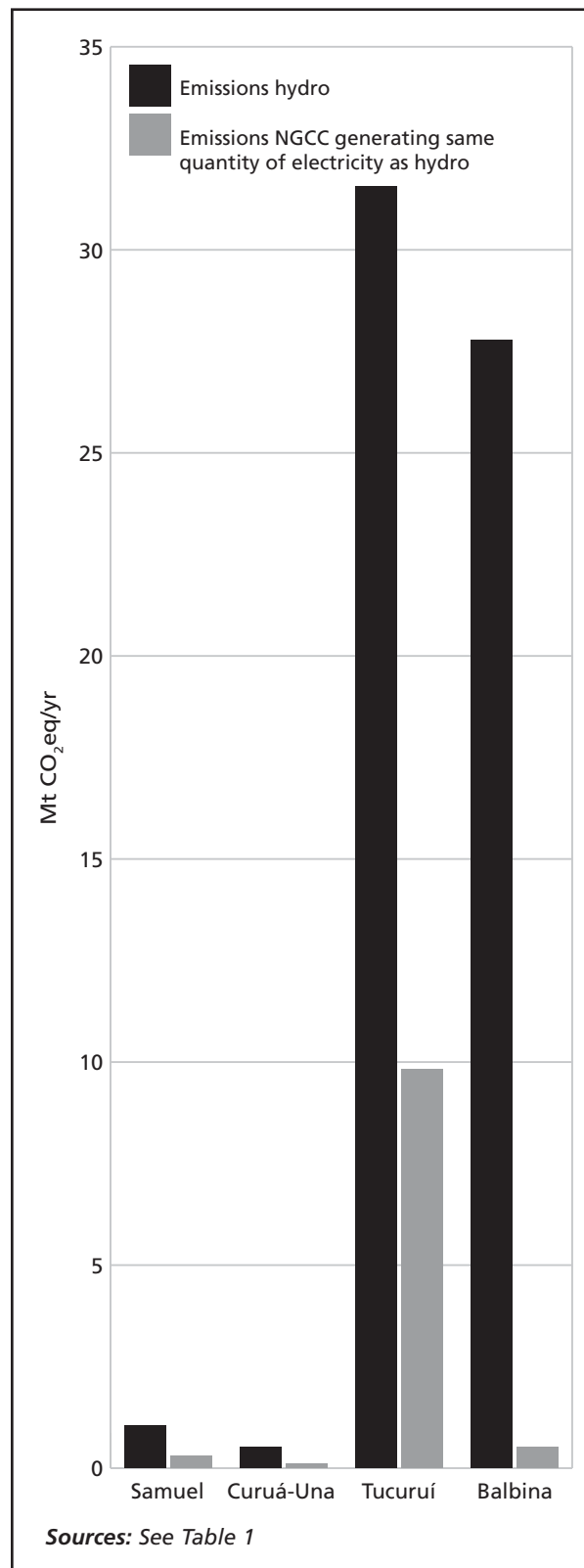
- Methane emissions occur due to bacteria that decompose organic matter in oxygen-poor water. The bottom layer of water in tropical reservoirs tends to be seriously depleted of oxygen. Some methane bubbles are oxidized to carbon dioxide as they rise to the reservoir surface – thus shallow tropical reservoirs where bubbles have less time to become oxidized tend to have the highest methane emissions.

- Emissions per unit of area flooded are much higher from tropical reservoirs than from those in boreal zones, which are in turn generally higher than those in temperate zones.

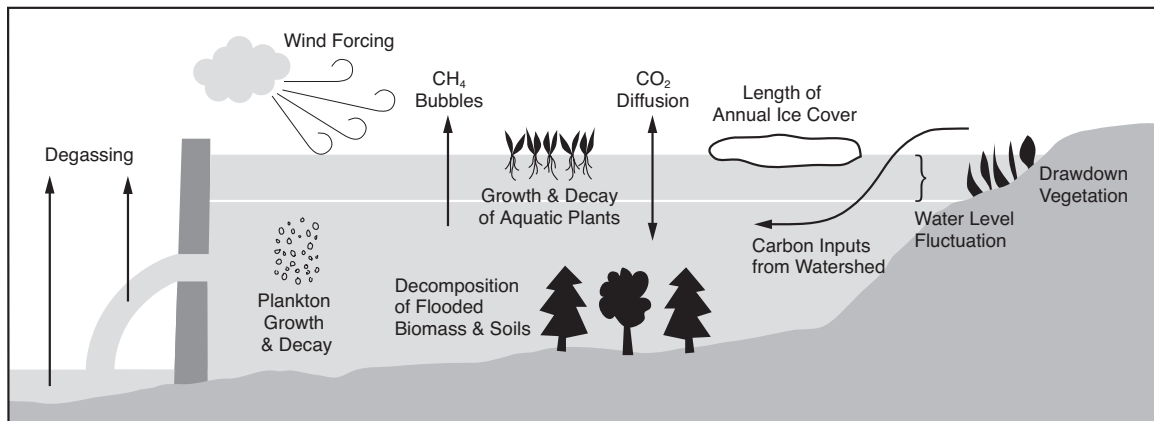
- Reservoirs emit greenhouse gases over their lifetime. There is an initial high pulse of emissions in the first few years after reservoir filling because of the huge amounts of carbon in the biomass and soils in the area flooded. Emissions generally appear to decline over subsequent decades. The actual rate of decline varies widely between individual reservoirs and climate zones. Some reservoirs fail to show any clear decline, and researchers have sometimes recorded increased emissions over time when sampling the same reservoir several years apart.<sup>21</sup>

- Emission levels vary widely between reservoirs depending upon such factors as the area and type of ecosystems flooded, reservoir depth and shape, the local climate, the duration of winter ice-cover, the area of the reservoir covered in aquatic plants, water quality (especially pH and nutrient content), the way in which the dam is operated, and the ecological, physical and socio-economic characteristics of the dammed river basin. Among the factors influencing degassing emissions are the

**FIGURE 2. “RESERVOIR NET” TROPICAL HYDRO EMISSIONS COMPARED TO NATURAL GAS COMBINED CYCLE GENERATION**



**FIGURE 3. SOME KEY FACTORS INFLUENCING RESERVOIR GHG EMISSIONS**



concentrations of methane at different reservoir depths, the depth of turbine and spillway intakes, and the type of spillway design.

- Surface emissions vary widely among different parts of the same reservoir (largely due to changes in depth, exposure to wind and sun, and growth of aquatic plants), and from year to year, season to season, and between night and day. This greatly complicates efforts to develop reliable whole-reservoir estimates from a limited set of samples measured at specific points in the reservoir during specific time periods. Confidence in the measurements themselves is also hampered by the different results obtained through different measuring equipment and techniques, and disagreements over which measuring methods are most appropriate.<sup>22</sup> Factors affecting degassing emission volumes include variations in the volume of water discharged, and the proportion of turbined water versus that which is spilled.

- Calculation of the warming impact of reservoirs should be based upon net emissions. This requires adjusting measurements of gross emissions at the reservoir surface and dam outlets to allow for whatever sinks and sources of greenhouse gases existed in the reservoir zone before submergence, the uptake of carbon through reservoir photosynthesis, and the impact of the reservoir upon the pre-dam flows of carbon throughout the wider watershed.

### **THE PAPER TIGER: NET VS. GROSS EMISSIONS**

One of the areas of strongest disagreement among reservoir emission researchers is how to quantify net emissions. The Hydro-Québec and COPPE teams repeatedly stress the importance of using net rather than gross emissions, and criticize independent researchers for not doing so. Yet they are attacking a paper tiger: Fearnside and others who believe that hydro emissions can be significant have repeatedly stressed the importance of net emissions. Indeed, the most comprehensive analyses of net emissions have been done by Fearnside – while Pinguelli Rosa has only presented data on gross emissions.

Fearnside, who is one of the world's leading experts on greenhouse gas fluxes from Amazonian ecosystems, takes account of the lost source of  $N_2O$  from flooded soils in his calculations, and of methane from forest termites. He also allows for the lost uptake of  $CO_2$  from forest vegetation and of  $CH_4$  from forest

| TABLE 2. GHG FLUXES AT THE AIR/WATER INTERFACE OF HYDROELECTRIC RESERVOIRS WORLDWIDE, DURING THE OPEN WATER PERIOD |                                   |                    |                                   |                                  |       |
|--|-----------------------------------|--------------------|-----------------------------------|----------------------------------|-------|
|  | Climatic zone<br>(size of sample) | Mean age<br>(year) | Range<br>(mg/m <sup>2</sup> /day) | Mean<br>(mg/m <sup>2</sup> /day) |       |
| Diffusive Fluxes   | CO <sub>2</sub>                   | Boreal (12)        | 24                                | 653 – 2,500                      | 1,459 |
|  |                                   | Temperate (16)     | 44                                | -1,195 – 2,200                   | 525   |
|  |                                   | Tropical (21)      | 13                                | -142 – 13,737                    | 5,467 |
|  | CH <sub>4</sub>                   | Boreal (7)         | 29                                | 3.5 – 22.8                       | 10.8  |
|  |                                   | Temperate (13)     | 49                                | 1.3 – 15.0                       | 6.7   |
|  |                                   | Tropical (22)      | 16                                | 5.7 – 800                        | 83.1  |
|  | N <sub>2</sub> O                  | Boreal (3)         | 18                                | 0.02 – 0.5                       | 0.2   |
|  |                                   | Temperate (0)      |                                   |                                  |       |
|  |                                   | Tropical (4)       | 8                                 | 0.15 – 9.6                       | 5.1   |
| Bubbling Fluxes  | CO <sub>2</sub>                   | Boreal (2)         | 10                                | 1.0                              | 1.0   |
|  |                                   | Temperate (1)      | 70                                | 1.0                              |       |
|  |                                   | Tropical (16)      | 14                                | 0.02 – 26                        | 2.5   |
|  | CH <sub>4</sub>                   | Boreal (5)         | 20                                | 0.04 – 184.2                     | 46.4  |
|  |                                   | Temperate (1)      | 70                                | 14                               |       |
|  |                                   | Tropical (21)      | 15                                | 0 – 800                          | 85.6  |
|  | N <sub>2</sub> O                  | Boreal (2)         | 27                                | 0 – 0.03                         | 0.02  |
|  |                                   | Temperate (0)      |                                   |                                  |       |
|  |                                   | Tropical (0)       |                                   |                                  |       |
| Blank entries = no data.<br><i>Source: Soumis et al. (2005).</i>   |                                   |                    |                                   |                                  |       |

soils. His calculations are conservative in that he mainly counts only methane emissions: he does not include CO<sub>2</sub> diffusing from the reservoir surface or degassing at the dam. This is because an unknown portion of these CO<sub>2</sub> emissions would be due to carbon originally taken up from the atmosphere by plankton and plants in the reservoir. Another part of these emissions would be due to carbon entering the reservoir from upstream which would also have been converted to CO<sub>2</sub> in the pre-dam river. The only CO<sub>2</sub> emissions included in Fearnside's calculations are those from the decay of the parts of flooded trees left standing above the reservoir level. Fearnside's methodology is not a complete net accounting, mainly because he does not include the impact of the reservoir upon carbon flows along the whole length of the river (see Box 1). For this reason his methodology can be termed "reservoir net."

Hydro proponents repeatedly imply that taking net emissions into account would always greatly reduce the apparent climate impact from reservoirs when only surface emissions are assessed.<sup>23</sup> Hydro-Québec, for example, claims that net emissions are probably 30-50% lower than gross.<sup>24</sup> The reality is much more complex. The ecosystems flooded by reservoirs are a mosaic of sources and sinks of carbon dioxide, methane and nitrous oxide (See Table 3). Natural lakes and rivers are usually sources of CO<sub>2</sub> and CH<sub>4</sub>. Northern peatlands are CO<sub>2</sub> sinks but usually CH<sub>4</sub> sources. Tropical wetlands can be major CH<sub>4</sub> sources and large CO<sub>2</sub> sinks. Forests and soils may be either sinks or sources of CO<sub>2</sub> and CH<sub>4</sub>. Tropical soils may

be either sources or sinks of N<sub>2</sub>O. Changes in local weather conditions mean that the same ecosystem can be a source one year, a sink the next.<sup>25</sup>

A team of Brazilian researchers led by Elizabeth Sikar has calculated fluxes of greenhouse gases before and after construction of Manso and Serra da Mesa dams in the Brazilian *cerrado* (savanna) ecosystems. Based on measurements taken in March 2004 (and not necessarily representative of other months or other years), the areas flooded by these dams would both have been CO<sub>2</sub> sources before impoundment. CO<sub>2</sub> emissions from Serra da Mesa reservoir were slightly lower than pre-dam emissions, and Manso reservoir was acting as a sink for carbon dioxide. Net CO<sub>2</sub> emissions from both reservoirs were thus negative.<sup>26</sup>

Sikar *et al.* found that the area flooded by Serra da Mesa had been a small source of CH<sub>4</sub> before dam construction, and that of Manso had been a small methane sink. At both sites the reservoirs created significant methane sources, Serra da Mesa emitting 100 times more CH<sub>4</sub> than before impoundment (not including degassing emissions). Both reservoirs turned nitrous oxide sinks into sources. The climate impact of the net N<sub>2</sub>O emissions at Serra da Mesa were almost two-thirds that of its net CH<sub>4</sub> emissions.<sup>27</sup> This is a potentially significant finding as N<sub>2</sub>O emissions have rarely been measured at tropical reservoirs and are usually assumed to be negligible.

Another assertion frequently made by Hydro-Québec and the International Hydropower Association is that because natural freshwater bodies are important CO<sub>2</sub> and CH<sub>4</sub> sources, reservoirs do not significantly increase emissions.<sup>28</sup> The logic behind this assertion is hard to find. If natural water bodies are significant GHG sources, then how is increasing the area of water bodies not adding GHG sources? This is like an arsonist setting fire to a forest and claiming he is not responsible for the CO<sub>2</sub> emissions caused, because natural forest fires release CO<sub>2</sub>.

Hydro proponents may be implying that reservoirs flood mostly areas that are already lakes and wetlands – which is not the case. As Fearnside has noted in response to criticism that he did not allow for pre-dam emissions from wetlands flooded under Tucuruí reservoir: “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.”<sup>29</sup>

The difference between net and gross emissions will vary widely between individual reservoirs according to the types of ecosystems inundated. In many cases, net emissions may be considerably lower than gross, in others net emissions may be higher. The latter will particularly be the case for tropical reservoirs when degassing emissions are added to gross reservoir surface emissions.

## DEGASSING EMISSIONS

As the Coke vs. *guaraná* dispute shows, the other main area of disagreement among reservoir emission researchers is the magnitude of degassing emissions at tropical dams. Significant methane degassing emissions were first measured immediately downstream of the Petit Saut dam. These downstream emissions were much greater than the total volume of methane emitted from the surface of Petit Saut’s reservoir.<sup>30</sup> The only other tropical dam where degassing has actually been measured and the results published is Balbina, in Brazil.

| TABLE 3. ESTIMATED GREENHOUSE GAS FLUXES (mg/CO <sub>2</sub> eq/m <sup>2</sup> /day) FOR DIFFERENT CLIMATIC ZONES AND ECOSYSTEMS |                 |                |                 |            |                  |               |                 |                 |                 |             |                  |               |                 |                 |                 |            |                  |               |                |
|--|-----------------|----------------|-----------------|------------|------------------|---------------|-----------------|-----------------|-----------------|-------------|------------------|---------------|-----------------|-----------------|-----------------|------------|------------------|---------------|----------------|
|  | Boreal          |                |                 |            |                  |               | Temperate       |                 |                 |             |                  |               | Tropical        |                 |                 |            |                  |               |                |
|  | CO <sub>2</sub> |                | CH <sub>4</sub> |            | N <sub>2</sub> O |               | CO <sub>2</sub> |                 | CH <sub>4</sub> |             | N <sub>2</sub> O |               | CO <sub>2</sub> |                 | CH <sub>4</sub> |            | N <sub>2</sub> O |               |                |
| Forest   | Mean            | -863           | -25             | 15         | -1,455           | -82           | 249             | -1,455          | -82             | 249         | -2,317           | -19           | 663             | -2,317          | -19             | 663        | -2,317           | -19           | 663            |
|  | Range           | -5,230 – 271   | -114 – 86       | 3 – 36     | -16,605 – 1,115  | -263 – -8     | -24 – 1,563     | -16,605 – 1,115 | -263 – -8       | -24 – 1,563 | -5,926 – 0       | -80 – 94      | 33 – 2,664      | -5,926 – 0      | -80 – 94        | 33 – 2,664 | -5,926 – 0       | -80 – 94      | 33 – 2,664     |
| Marsh/<br>Swamp  | Mean            |                | 57              |            |                  | 5,914         | 337             |                 | 5,914           | 337         | -5,688           | 4,513         | 83              | -5,688          | 4,513           | 83         | -5,688           | 4,513         | 83             |
|  | Range           |                |                 |            |                  | -190 – 24,668 |                 |                 | -190 – 24,668   |             | -11,634 – 3,443  | -127 – 14,294 |                 | -11,634 – 3,443 | -127 – 14,294   |            | -11,634 – 3,443  | -127 – 14,294 |                |
| Peatland   | Mean            | -744           | 2,131           | 1          | 703              | 8,488         |                 | 703             | 8,488           |             |                  | 11,132        |                 |                 | 11,132          |            |                  |               | 11,132         |
|  | Range           | -2,750 – 502   | -38 – 12,270    | -9 – 21    | -540 – 2,400     | 607 – 22,074  |                 | -540 – 2,400    | 607 – 22,074    |             | 8,096 – 16,445   |               | 8,096 – 16,445  |                 | 8,096 – 16,445  |            | 8,096 – 16,445   |               | 8,096 – 16,445 |
| Lakes  | Mean            | 1,304          | 2,621           | 20         | 1,886            | 489           |                 | 1,886           | 489             |             | -734             | 3,749         |                 | -734            | 3,749           |            | -734             | 3,749         |                |
|  | Range           | -1,745 – 2,698 | 324 – 3,518     | -192 – 304 | -1,116 – 2,921   | 31 – 1,288    |                 | -1,116 – 2,921  | 31 – 1,288      |             | -1,232 – -52     | 1,219 – 7,544 |                 | -1,232 – -52    | 1,219 – 7,544   |            | -1,232 – -52     | 1,219 – 7,544 |                |

Blank entries = no data.

**Sources:**  
 Forest, Marsh/Swamp, Peatland – Tremblay et al. (2005b) Table 4.7.  
 Lakes –  
 Boreal (Canada) – Tremblay et al. (2005b) Table 8.1.  
 Temperate CO<sub>2</sub> (Southwest US) – Therrien et al. (2005) Table 9.1.  
 Temperate CH<sub>4</sub> (Wisconsin) – Bastviken (2004).  
 Tropical CH<sub>4</sub> (Venezuela) – Engle and Melack (2000).  
 Tropical CO<sub>2</sub> (French Guyana) – Tremblay et al. (2005b) Table 8.7.

## Box 1. Rivers, Dams and Biogeochemical Cycles

Rivers play an important, although still poorly quantified, role in the global cycles of carbon and nutrients such as nitrogen, iron and silicon. These cycles help regulate the concentration of CO<sub>2</sub> in the atmosphere. By interrupting these cycles, dams could have a significant climate impact above and beyond that from their reservoir emissions.

When a river is dammed, much of the sediments and nutrients that it carries – in many cases more than 90% – will be trapped behind the dam wall. Globally dams are estimated to have reduced sediment discharge to the oceans by a quarter. The sediments that build up in reservoirs and gradually reduce their useful lives contain large amounts of carbon. The hydro industry has recently used this to argue that reservoirs are a major carbon sink.<sup>1</sup> Tracking the actual fate of the carbon that enters a reservoir, and establishing what its climate impact would have been in the absence of the reservoir, is however much more complex than the International Hydropower Association assumes.

Much of the carbon in sediments is in fact converted into CO<sub>2</sub> and CH<sub>4</sub> in the reservoir<sup>2</sup> (a major reason for the net warming impact of reservoirs is that they convert into CH<sub>4</sub> carbon which would have “naturally” been emitted as CO<sub>2</sub>). Research on a 70-year old Quebec reservoir implies that shoreline erosion due to waves and the rise and fall of the reservoir may mobilize large quantities of carbon from flooded soils and sediments.<sup>3</sup> Some of this carbon is likely to be converted into CO<sub>2</sub> and CH<sub>4</sub> and emitted at the reservoir surface, and some washed downstream.

The loss of nutrients to inshore waters because of dams may have a significant climate impact. Nutrients from rivers are important in fertilizing oceanic plankton. Plankton in turn plays a major role in absorbing CO<sub>2</sub> from the atmosphere. (The IPCC estimates that in the absence of oceanic plankton, atmospheric CO<sub>2</sub> concentrations would be 55% higher than present levels).<sup>4</sup>

The nitrates and phosphates trapped in reservoirs are more than compensated for by the run-off into rivers of agricultural fertilizers, sewage and industrial pollution. The same is not true for trapped silicates, which have no significant man-made source. Silicates stimulate the production of silica-shelled plankton known as diatoms. Diatoms are more efficient at carbon sequestration than non-siliceous plankton and, according to Venugopalan Ittekkot, director of the Centre for Tropical Marine Ecology in Bremen, “play a crucial role in the biological uptake of carbon dioxide by the ocean.”

Ittekkot has found that diatom blooms in the Bay of Bengal are fertilized by the surge of nutrients entering the bay from the Ganges-Brahmaputra river system during the monsoon. Ittekkot believes that the sediments washed into the bay along with the Ganges-Brahmaputra floodwaters also accelerate the rate at which diatoms and the organic carbon they contain fall to the sea floor. The sediments stick to the diatoms and act as tiny ballasts, dragging the diatoms downward.<sup>5</sup>

### Sources:

1. International Hydropower Association (undated)
2. Adams (2005).
3. Houel et al. (2006).
4. Parekh (2004).
5. Ittekkot et al. (2000).



Fearnside has modeled degassing of methane at Tucuruí, Samuel, Curuá-Una and Balbina dams. His estimates are based on measurements of methane concentrations in the reservoirs combined with assumptions based upon the data from Petit Saut. Fearnside calculates that degassing emissions at Tucuruí were responsible for as much as 75% of its total climate impact in 1990 (six years after the reservoir began filling) (see Table 1).<sup>31</sup> Fearnside estimates that degassing emissions from another Amazonian dam, Samuel, accounted for 94% of its climate impact in 1990.<sup>32</sup>

Fearnside's degassing figures, especially for Tucuruí, have been repeatedly criticized as major overestimates by Pinguelli Rosa and his colleagues.<sup>33</sup> Pinguelli Rosa argues that a uniquely high proportion of dissolved methane is degassed at Petit Saut due to its aeration weir, so extrapolations should not be made from Petit Saut to predict degassing emissions elsewhere. Fearnside argues that while the weir does contribute to the very high rate of degassing at Petit Saut (89% of the methane passing through the turbines is degassed), the drop in pressure acting on the water passing through turbines at the other dams is sufficient to lead to a substantial methane release. Fearnside assumes this release to be 56% of dissolved methane in the turbinated water at Tucuruí and 60% at the other two dams. At Tucuruí, Fearnside calculates that more than 40% of the degassing emissions are from the spillway. Tucuruí has a ski-jump type spillway, where water is shot up from the foot of the spillway then crashes into a concrete-lined basin. Fearnside argues that this spillway acts as an extremely effective aeration device and causes all dissolved CH<sub>4</sub> to be released.<sup>34</sup>

Fearnside's assumptions for turbine degassing recently received empirical support from measurements made at Balbina dam in the central Amazon by a team led by a colleague at INPA. The team found that 60% of the methane passing through Balbina's turbines was released to the atmosphere downstream – making Fearnside's assumptions appear to be reasonable, and even slightly conservative for Tucuruí.<sup>35</sup>

Pinguelli Rosa *et al.* claim to recognize that degassing emissions occur at Tucuruí, have proposed a research program to measure the extent of the emissions, and have stated several times that degassing should be included in calculations of reservoir emissions. Yet they fail to make any allowance for degassing emissions in their own calculations of the magnitude of reservoir emissions – while berating Fearnside for including degassing.

Stanford University's Cullenward and Victor, in their *Climatic Change* Editorial Comment on the Fearnside/Pinguelli Rosa skirmish, largely support Fearnside's degassing methodology. They criticize Pinguelli Rosa *et al.* for offering no explanation to back their assumption that most of the methane would stay dissolved after undergoing a major drop in pressure and thus solubility.

## **OTHER DAM IMPACTS ON CARBON FLUXES**

A complete net life-cycle analysis of the warming impact of hydropower would need to consider various factors other than those considered in Fearnside's reservoir net methodology. However, at least for tropical reservoirs, including these factors would likely not require a significant adjustment to reservoir net emissions. This is largely because the impact of the reservoir's role as a factory for converting carbon into the powerful greenhouse gas methane (and in at least some cases for producing the even more powerful gas nitrous oxide) will likely far outweigh other impacts over the long term.

## Box 2. The Hazards of Comparing Gases

Comparing the contribution to global warming from emissions of different greenhouse gases is fraught with complications. Molecules of separate gases have different lifetimes in the atmosphere, trap varying amounts of heat, and react with other gases in different ways. The multiplier commonly used to convert the impact of methane and nitrous oxide into “carbon dioxide equivalent” (CO<sub>2</sub>eq) units is known as the Global Warming Potential (GWP).

The Kyoto Protocol uses a 100-year GWP of methane of 21 and of nitrous oxide of 310. The IPCC revised the 100-year GWP for methane up to 23 in 2001 but this revision has not been adopted by the Protocol. The GWP methodology is controversial for a number of reasons and several alternative indices have been proposed, including by Pinguelli Rosa and Fearnside.

The GWP represents the cumulative warming impact after 100 years of a one-time pulse into the atmosphere of a ton of methane compared to a ton of carbon dioxide. But methane emissions from reservoirs do not occur as a one-time pulse but as a flow varying in volume over the lifetime of the reservoir.

Stuart Gaffin from Columbia University has developed a model for evaluating the warming impact of continuous emissions of methane. Philip Raphals of the Helios Centre in Montreal has used this model to calculate that the cumulative global warming effect after 100 years of a constant methane emitter is 39.4 times greater than that of a constant emitter of an equivalent weight of carbon dioxide.

Methane, especially in the tropics, is a significant component of reservoir emissions. The value of the methane multiplier used will thus have a large impact on the estimate of a reservoir’s total contribution to climate change. Almost all estimates for the warming impact of reservoirs are based on the now-outdated methane GWP of 21. Using a larger methane multiplier would increase the estimated global warming impact of reservoirs.

Because of the general acceptance of the methane GWP of 21, and in particular because of its use by the Kyoto Protocol, 21 is the methane multiplier used for the calculations in this paper.

*Further Reading: Raphals (2001).*

A life-cycle analysis of the climate impact of reservoirs should include the impacts of dam construction and decommissioning. Dam construction causes GHG emissions due to the use of fossil fuels by machinery and the production of building materials, in particular cement. Construction emissions vary according to the size and type of dams, with gravity dams (which contain a huge volume of concrete) having the highest emissions. Construction emissions could make up a significant component of the life-time emissions from a boreal dam, but would likely be insignificant compared to total emissions from a tropical project.<sup>36</sup>

Dam decommissioning is likely to result in the mobilization of a significant amount of accumulated sediments, potentially leading to a large pulse of carbon emissions. The growth of vegetation on the mudflats exposed by draining a reservoir, however, would be a carbon sink.<sup>37</sup> (See Box 1 for more on the potential impacts of dams on watershed-wide carbon fluxes.)

Emissions from human activities resulting from dam construction are potentially significant although these have not yet been calculated for any project (and would be very difficult to accurately ascribe to a particular

dam). These secondary emissions include deforestation caused by farmers displaced to make way for the reservoir, and by farmers and developers clearing forests along access roads built for dam construction. Dams with an irrigation component may lead to increased methane emissions from newly watered farmland.

## EMISSIONS OVER TIME

Yet another layer of complexity when assessing reservoir emissions is how these may change over time. The usual assumption made about the pattern of reservoir emissions is that there is a large initial pulse of both CO<sub>2</sub> and CH<sub>4</sub> immediately after reservoir filling, followed by a gradual decline. At Petit Saut, methane emissions during the first year after filling the reservoir are estimated to represent around a quarter of the methane that would be released over the next century of the reservoir's life.<sup>38</sup> It is not clear if N<sub>2</sub>O emissions decline over time.<sup>39</sup>

The actual rate of decline of GHG fluxes can vary widely between individual reservoirs. For many of the reservoirs studied, no obvious pattern of decline can be seen, especially for methane.<sup>40</sup> Some of the highest methane emissions measured from a Brazilian reservoir came from a 36-year-old project (Três Marias). The conditions for generating methane in tropical reservoirs continue over the life of the reservoir. Thus there is a strong theoretical basis for believing that after the initial pulse has subsided, substantial methane emissions will continue from a tropical reservoir until it is decommissioned.<sup>41</sup>

Hydro-Québec states that CO<sub>2</sub> emissions from boreal reservoirs fall to the levels of natural lakes found in the same basin within 10 years, and CH<sub>4</sub> levels within four years.<sup>42</sup> A close look at Hydro-Québec's actual data, however, reveals a different story: average emissions for 26 Québécois reservoirs ranging in age from 10 to 75 years show CO<sub>2</sub> emissions 50% higher than average lake emissions; CH<sub>4</sub> emissions more than 14 times higher; and N<sub>2</sub>O emissions almost twice as high.<sup>43</sup> Other researchers in Québec also report higher CO<sub>2</sub> emissions from reservoirs up to 70 years old than those from natural lakes.<sup>44</sup> In any case, declining to natural lake emission levels does not mean declining to pre-dam levels: lakes can be substantial GHG producers and would normally be larger emitters than the ecosystems inundated by the dam (natural lakes cover around 2.3% of the world's continental surface area yet are estimated to produce 6-16% of natural methane emissions).<sup>45</sup>

## RESERVOIR GAS VS. NATURAL GAS

Table 1 shows available estimates for the emissions in grams of carbon dioxide equivalent (CO<sub>2</sub>eq) per kilowatt-hour of specific hydropower plants using several different methodologies (see Box 2 for an explanation of the conversion of CO<sub>2</sub> into CO<sub>2</sub>eq). Comparing the hydro plants with the non-hydro generating sources given in Table 4 indicates that boreal hydropower has a far lower climate impact than fossil fuel alternatives, but tropical hydropower can have an impact much worse than even the dirtiest fossil-fuel plants. The tropical hydropower emissions listed are only for a single year and so not necessarily representative of their life-time emissions. As most of the emission estimates are for a year after the high initial pulse there is no reason to believe that they systematically over- or under-estimate long-term average emissions.

| <b>TABLE 4. LIFE-CYCLE GREENHOUSE GAS EMISSIONS FROM NON-HYDRO GENERATION TECHNOLOGIES</b> |  |                |
|--|--|----------------|
|  | <b>Range<br/>(gCO<sub>2</sub>eq/kWh)</b> | <b>Average</b> |
| <b>Coal (modern plant)</b>   | 959 – 1,042 <sup>a</sup>                 | 1,000          |
| <b>IGCC (coal)</b>   | 763 – 833 <sup>b</sup>                   | 798            |
| <b>Diesel</b>  | 555 – 880 <sup>c</sup>                   | 717            |
| <b>Natural gas combined-cycle (NGCC)</b>   | 469 – 622 <sup>d,e</sup>                 | 545            |
| <b>Photovoltaic</b>  | 12.5 – 104 <sup>f</sup>                  | 58             |
| <b>Wind turbines</b>   | 7 – 22 <sup>f</sup>                      | 14             |

**Sources:**  
*a Spath et al. (1999).*  
*b Gibbins (2005).*  
*c IEA Implementing Agreement for Hydropower (2000).*  
*d Spath and Mann (2000).*  
*e Meier (2002).*  
*f World Energy Council (2004).*

Net reservoir emissions from Balbina dam in the middle of Amazonia are exceptionally high – Fearnside estimates that in 1990, three years after reservoir-filling, Balbina had an impact on global warming higher than that of 54 modern gas plants generating the same amount of electricity. Conversely, gross emissions from Itaipú – the world’s second largest power plant after China’s Three Gorges dam – are only 1% of those from equivalent natural gas generation.

Balbina’s reservoir is shallow and submerged a huge area to generate a relatively small amount of electricity. Itaipú has a deep reservoir and flooded a small area relative to its huge generation capacity. The relationship between power capacity and area flooded has been termed “power density,” expressed in watts per square meter. Table 1 shows that reservoir emissions generally decline with increasing power density. Table 5 gives power densities for a selection of dams that have recently been completed or are under construction or proposed.

It is noteworthy that the average gross emission per kilowatt-hour of the nine hydro projects studied by COPPE is slightly higher than that of a comparable gas plant, and that four of these nine reservoirs show higher emissions than natural gas. Were degassing emissions to be included, five out of the nine hydro would show higher emissions than a combined-cycle gas plant, and the average emission would be substantially higher than natural gas. Pinguelli Rosa *et al.* are therefore on weak ground when they conclude that “the figures for the hydro-power plants are better, in most cases.”<sup>46</sup>

Table 1 shows the average climate impact of Petit Saut dam over its first 20 years to be nearly five times that of a gas plant. Such a comparison is more relevant than that made by the team of researchers led by Robert Delmas who have studied Petit Saut, and who state that the dam has a lower warming impact than gas, coal and oil plants *over a 100-year period*. Delmas *et al.* predict that after 57 years the cumulative

| <b>TABLE 5. POWER DENSITIES OF SOME PROPOSED, UNDER CONSTRUCTION, AND RECENTLY COMPLETED DAMS</b> |              |                    |                                |                                      |  |
|---|--------------|--------------------|--------------------------------|--------------------------------------|--|
| <b>Dam</b>  | <b>River</b> | <b>Country</b>     | <b>Installed Capacity (MW)</b> | <b>Area Flooded (km<sup>2</sup>)</b> | <b>Power Density (W/m<sup>2</sup>)</b> |
| Bujagali  | Nile         | Uganda             | 250                            | 4                                    | 62.50                                  |
| Tehri   | Bhagirathi   | India              | 2,000                          | 42                                   | 47.62                                  |
| Three Gorges  | Yangtze      | China              | 18,200                         | 1,100                                | 16.55                                  |
| Ralco   | Bio Bio      | Chile              | 570                            | 35                                   | 16.29                                  |
| Mphanda Nkuwa   | Zambezi      | Mozambique         | 1,300                          | 100                                  | 13.00                                  |
| Tipaimukh   | Barak        | India              | 1,500                          | 284                                  | 5.28                                   |
| La Parota   | Papagayo     | Mexico             | 900                            | 173                                  | 5.20                                   |
| Sardar Sarovar  | Narmada      | India              | 1,450                          | 376                                  | 3.86                                   |
| Ilisu   | Tigris       | Turkey             | 1,200                          | 313                                  | 3.83                                   |
| Pak Mun   | Mun          | Thailand           | 136                            | 49                                   | 2.78                                   |
| Belo Monte/<br>Babaquara Complex  | Xingu        | Brazil             | 17,769                         | 6,580                                | 2.70                                   |
| Merowe  | Nile         | Sudan              | 1,250                          | 476                                  | 2.63                                   |
| Nam Theun 2   | Nam Theun    | Laos               | 1070                           | 450                                  | 2.38                                   |
| Yacyretá*   | Paraná       | Argentina/Paraguay | 3,100                          | 1,720                                | 1.80                                   |
| Polavaram   | Godavari     | India              | 960                            | 637                                  | 1.51                                   |
| Indira (Narmada) Sagar  | Narmada      | India              | 1,000                          | 908                                  | 1.10                                   |
| Lom Pangar  | Lom          | Cameroon           | 51                             | 610                                  | 0.08                                   |

*\* If reservoir filling completed*  
*N.B. Shading added to show application of CDM Executive Board power density categories (see Box 3).*

warming impact of a natural gas plant would start to exceed that of Petit Saut, with its high initial, but later declining, emissions.<sup>47</sup>

It is, however, highly unrealistic to think that we will still be using today's natural gas power generation technology six decades in the future. Concern over global warming, rising fuel prices (and declining supply), and technological improvements will surely mean that thermal power-plant efficiency will improve in the coming decades. It may also be standard practice for fossil plants to capture and sequester their carbon emissions within a decade or two. It is also likely – and necessary in climate terms – that fossil fuel plants will over the coming decades increasingly be replaced by renewable, low-carbon alternatives. It certainly makes little sense to assume that the main alternative to hydropower throughout the next century will be today's coal, oil or gas plants.

## **INCOMPLETE INVENTORIES**

Countries are required to produce detailed inventories of their sources and sinks of greenhouse gases under the UN climate convention and the Kyoto Protocol. The original guidelines for these inventories

### Box 3. Hydropower and the Clean Development Mechanism

Hydropower is the second most common type of project proposed to receive carbon credits under the Kyoto Protocol's Clean Development Mechanism. As of September 2006, 191 hydro projects were in the CDM's project pipeline, of which 14 had been issued with credits.

The mechanism's Executive Board issued its first ruling relevant to reservoir emissions in February 2006. This states that hydros with power densities (PDs) greater than 10 watts per square meter can use one of the methodologies already approved for calculating project-specific emission reductions. These hydros do not need to account for reservoir emissions. Hydros with PDs between 4 and 10 W/m<sup>2</sup> can also use currently approved methodologies, but must presume reservoir emissions of 90 grams of CO<sub>2</sub>eq for each kWh generated. Hydros with PDs of 4 W/m<sup>2</sup> or under cannot use any of the currently approved methodologies.

A developer intending to apply for carbon credits for a hydro project with a PD of 4 W/m<sup>2</sup> or less will thus have to submit a new methodology and get it approved by the CDM's Methodology Panel. The Executive Board has sent a signal that such a methodology would have to allow for reservoir emissions, and at a rate higher than 90 gCO<sub>2</sub>eq/kWh. There is still no clarity as to what rate would be acceptable to the Executive Board or how they would decide upon this.

The board's choices of the PDs and emissions numbers are presumably based on the COPPE data. (The current chair of the Executive Board, José Domingos Miguez, is head of the climate sector of the Brazilian Ministry of Science and Technology (MCT), with which COPPE works closely. Miguez is on record as saying that the ministry requested Eletrobrás to commission the COPPE studies because of concerns that Fearnside's work had led to the issue "becoming political" and could lead to Brazil being pressured to take on a future

commitment to reduce emissions). Sources close to the board indicate that the choice of the actual thresholds chosen to distinguish between the three classes of hydros, and the 90 grams of CO<sub>2</sub>eq emission factor, were largely arbitrary (given the scarcity of data any generic approach to hydro emissions based on PDs will of necessity be largely arbitrary).

Comparing these numbers with the power densities and emissions of hydros in Table 1 it can be seen that the Executive Board's approach would exclude (for now) the worst hydro emitters. However PDs are only a rough proxy for emissions per kWh, and there is no reason to believe that a tropical hydro with a PD between 4 and 10 could not have emissions greatly exceeding 90 gCO<sub>2</sub>eq/kWh. It would therefore be prudent to rule that hydros with a PD less than ten cannot sell credits pending more data on the relationship between PDs and emissions

Hydropower projects have already been subject to quality criteria within the CDM, although not by the mechanism's Executive Board. The European Union's "Linking Directive" requires hydropower projects above 20 MW capacity to respect the World Commission on Dam's "criteria and guidelines" if they are to generate CDM credits to be used for compliance in Europe's carbon trading system. The German and Dutch governments also require large hydro projects from which they buy CDM credits to comply with the WCD. However no attempt has yet been made to show WCD compliance for any hydro applying for carbon credits. Some large hydros that clearly do not meet WCD criteria, such as Bujagali in Uganda and Jorethang Loop in Sikkim, India, are currently in the process of applying for CDM credits.

*Sources: CDM project data from [cd4cdm.org](http://cd4cdm.org) (the most common project type is biomass energy). Miguez quoted in Fearnside (2004a). For more on the WCD see [www.dams.org](http://www.dams.org) and [www.irn.org/wcd](http://www.irn.org/wcd).*



did not require an accounting of reservoir emissions. Excluding reservoirs from inventories likely significantly under-represents the actual contribution to climate change of some countries, especially of those in the tropics with large reservoir areas such as Brazil.<sup>48</sup>

A new set of guidelines on how to complete national inventories was agreed upon, after much debate, at an Intergovernmental Panel on Climate Change meeting in Mauritius in April 2006. These guidelines will require countries to include CO<sub>2</sub> emissions from reservoirs under the category of “flooded land.”<sup>49</sup> Unfortunately it will not be obligatory to account for methane emissions.

Whether and how to include reservoirs in inventories was one of the most contested issues during the three years of research and negotiations needed to complete the new guidelines. Although the inclusion of reservoirs under the category of “flooded land” was agreed by the IPCC’s scientific experts, Brazilian government officials (supported by Austria and Norway) tried to remove reservoirs from the guidelines at the IPCC’s Mauritius meeting. Canada (supported by the US) opposed removing reservoirs.<sup>50</sup>

Eventually a compromise was reached whereby inventories will in the future have to account for the CO<sub>2</sub> emissions due to carbon in the biomass initially flooded by reservoirs. Carbon dioxide fluxes from the reservoir surface and methane emissions will not have to be measured. Treatment of these issues was relegated to appendices, meaning that while they may be considered, their inclusion is not mandatory. While countries will now have to count reservoirs as carbon dioxide sources, much of the warming impact of tropical dams will be missed because their methane emissions do not have to be inventoried.

## RECOMMENDATIONS

- The governments that have ratified the UN Framework Convention on Climate Change (i.e. the Conference of Parties) should commission the IPCC to produce a Special Report on reservoir emissions. Cullenward and Victor point out that the 2005 IPCC Special Report on CO<sub>2</sub> capture and storage offers a useful model.<sup>51</sup>
- Although it is not obligatory to include methane emissions from reservoirs in GHG inventories to be submitted to the UN, countries with the scientific capacity should include these emissions using the methodologies in the relevant appendix of the IPCC’s 2006 guidelines. Methane emissions should be included in the obligatory methodologies for the next version of the IPCC’s guidelines (which hopefully would be based upon an IPCC Special Report).
- Pending clarification of the link between power densities and specific emissions levels from the IPCC, the CDM Executive Board should amend its 2006 decision on hydropower emissions to rule that hydros with a power density less than ten are not eligible for credits.

## END NOTES

- <sup>1</sup> Estimate of number of reservoirs ( $>0.01\text{km}^2$ ) from Downing et al. (2006). Only a very small proportion of all reservoirs have a hydropower component. Around 20% of the world's c.45,000 large dams ( $>15\text{m}$  high) generate electricity (Tremblay et al. (2005a), p.23), however the percentage of small dams with a hydro component should be much lower than 20%.
- <sup>2</sup> St. Louis et al. (2000) estimate that reservoirs worldwide release 70 million tons  $\text{CH}_4$  and 1,000 million tons  $\text{CO}_2$  annually (20% of estimated  $\text{CH}_4$  emissions from all other human activities, and 4%  $\text{CO}_2$  from other known anthropogenic sources). These estimates are based on a calculation of 1.5 million  $\text{km}^2$  global reservoir area (0.9m  $\text{km}^2$  temperate; 0.6m  $\text{km}^2$  tropical). This calculation is likely an overestimate. A more recent analysis estimates that reservoirs ( $>0.01\text{km}^2$ ) cover a global area of 260,000  $\text{km}^2$  (Downing et al. (2006)).
- <sup>3</sup> Cullenward and Victor (2006).
- <sup>4</sup> Thomson Essential Science Indicators ([www.esi-topics.com](http://www.esi-topics.com)).
- <sup>5</sup> Rosa et al. (2004).
- <sup>6</sup> Rosa et al. (2005).
- <sup>7</sup> Rosa et al. (2004); Fearnside (2004a); Rosa et al. (2005); Fearnside (2006).
- <sup>8</sup> Rudd et al. (1993); Kelly et al. (1994).
- <sup>9</sup> Rosa et al. (1994); Fearnside (1995).
- <sup>10</sup> See Rosa and Santos (2000), pp.7-8.
- <sup>11</sup> Duchemin is one of the leading-authors of the 2006 IPCC Guidelines for National GHG Inventories.
- <sup>12</sup> McCully (2002). This publication, which was largely based upon the work of Fearnside and Duchemin, was sharply criticized by Rosa et al. (2002?) and Hydro-Québec's Luc Gagnon (2002).
- <sup>13</sup> E.g. Tremblay, Lambert and Demers (2005); Tremblay and Schetagne (2006).
- <sup>14</sup> Duchemin pers. com.
- <sup>15</sup> Most of the sampling has been done by Hydro-Québec in Canada and the South-Western US. See Tremblay et al. (2005b), p.210; Therrien et al. (2005), p.234.
- <sup>16</sup> For a helpful summary of the science see Soumis et al. (2005).
- <sup>17</sup> Soumis et al. (2005); Sikar et al. (2005).
- <sup>18</sup> Soumis et al. (2004); Tremblay et al. (2005b).
- <sup>19</sup> Galy-Lacaux et al. (1999).
- <sup>20</sup> Soumis et al. (2004); Sikar et al. (2005).
- <sup>21</sup> Santos (2000); Soumis et al. (2005).
- <sup>22</sup> See e.g. Lambert and Fréchette (2005).
- <sup>23</sup> See e.g. International Hydropower Association (undated).
- <sup>24</sup> Tremblay et al. (2005c), p.658.
- <sup>25</sup> See e.g. Blaise et al. (2005); Tremblay et al. (2005c).
- <sup>26</sup> Sikar et al. (2005). Sikar's team measured emissions from the reservoirs and estimated pre-reservoir emissions by extrapolating from fluxes measured from areas near each reservoir.
- <sup>27</sup> Sikar et al. (2005).

- <sup>25</sup> See e.g. IHA (undated).
- <sup>29</sup> Fearnside (2002), p.83.
- <sup>30</sup> Galy-Lacaux et al. (1999).
- <sup>31</sup> Fearnside (2002).
- <sup>32</sup> Fearnside (2005a). Fearnside calculates that degassing accounted for only 9% of Balbina's warming impact in 1990. This is because reservoir filling only occurred in 1987 so emissions from above-water decay of the huge area of forest flooded by Balbina were still extremely high in 1990 (Fearnside (2004b)).
- <sup>33</sup> Fearnside's reservoir net emissions calculation for Samuel is actually less than COPPE's gross emissions estimate – see Table 1.
- <sup>34</sup> Fearnside (2002), p.81.
- <sup>35</sup> Kemenes, A. et al. (2006).
- <sup>36</sup> See e.g. Svensson (2005), p.35; Pacca (2003).
- <sup>37</sup> See e.g. Pacca (2003).
- <sup>38</sup> Delmas et al. (2005).
- <sup>39</sup> Tremblay et al. (2005b), p.229.
- <sup>40</sup> Soumis et al. (2004); Soumis et al. (2005); Rosa et al. (2005); Matthews et al. (2005)
- <sup>41</sup> Reservoir sedimentation could over time increase CH<sub>4</sub> emissions if it creates large expanses of marshy areas in the former reservoir.
- <sup>42</sup> Tremblay et al. (2005c).
- <sup>43</sup> Tremblay et al. (2005c), Tables 8.1 and 8.8.
- <sup>44</sup> Soumis et al. (2004).
- <sup>45</sup> 3 million km<sup>2</sup> lake surface emitting 8-48 Tg CH<sub>4</sub> per year (Bastviken et al. (2004)).
- <sup>46</sup> Rosa et al. (2004), p.18.
- <sup>47</sup> Delmas et al. (2005), p.303.
- <sup>48</sup> Applying the average gross emissions per dam from the COPPE data to all of Brazil's 144 large hydros gives an indicative estimate of total emissions from Brazilian hydro of more than 285 million tons CO<sub>2</sub>eq (not including the contribution of N<sub>2</sub>O). For the three dams for which both present data, Fearnside's reservoir net estimates are on average 78% higher than COPPE's gross estimates. Using this percentage to convert gross to reservoir net gives a total for Brazilian hydro emissions of 507 million tons CO<sub>2</sub>eq – 38% of the figure given in the Brazilian government's inventory for emissions of CO<sub>2</sub> and CH<sub>4</sub> from all sources in 1994 (listing of Brazilian hydro projects and data for Curuá-Una used to generate the 78% figure in Santos (2000); Brazilian inventory data from Ministério da Ciência e Tecnologia (2004)). This extrapolation is problematic but illustrates the potential scale of undercounting due to neglecting reservoir emissions in emission inventories. Accounting for reservoir emissions could increase Canada's estimated greenhouse gas output by around 3%, and the country's electrical sector emissions by around 17% (Duchemin et al. (2002)).
- <sup>49</sup> "Flooded land" is included in the wetlands chapter of the volume of the guidelines on Agriculture, Forestry and Other Land Use (AFOLU). See [www.ipcc-nggip.iges.or.jp/public/2006gl/ppd.htm](http://www.ipcc-nggip.iges.or.jp/public/2006gl/ppd.htm).
- <sup>50</sup> *Earth Negotiations Bulletin* 12:295, 1 May 2006. The International Hydropower Association lobbied the IPCC and government officials against "flooded lands" staying in the guidelines (*IHA Newsletter*, July 2006).
- <sup>51</sup> The IPCC was requested to study CSS by COP7 in 2001.

## BIBLIOGRAPHY

- Adams, D.D. (2005) 'Diffuse flux of Greenhouse Gases – Methane and Carbon Dioxide – at the Sediment-Water Interface of Some Lakes and Reservoirs of the World.' In Tremblay et al.
- Blais, A.-M. et al. (2005) 'Greenhouse Gas Fluxes (CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O) in Forests and Wetlands of Boreal, Temperate and Tropical Regions.' In Tremblay et al.
- Bastviken, D. et al. (2004) 'Methane emissions from lakes: Dependence of lake characteristics, two regional assessments, and a global estimate,' *Global Biogeochemical Cycles* 18.
- Delmas, R. et al. (2005) 'Long Term Greenhouse Gas Emissions from the Hydroelectric Reservoir of Petit Saut (French Guiana) and Potential Impacts.' In Tremblay et al.
- Duchemin, É., et al. (2002) 'Hydroelectric reservoirs as an anthropogenic source of greenhouse gases,' *World Resource Review* 14.
- Downing, J.A. et al. (2006) 'The global abundance and size distribution of lakes, ponds, and impoundments,' *Limnology and Oceanography* 51:5.
- Engle, D. and Melack, J.M. (2000) 'Methane emissions from an Amazon floodplain lake: Enhanced release during episodic mixing and during falling,' *Biogeochemistry* 51:1.
- Fearnside, P.M. (1995) 'Hydroelectric Dams in the Brazilian Amazon as Sources of "Greenhouse" Gases,' *Environmental Conservation* 22:1.
- Fearnside, P.M. (1997) 'Greenhouse-Gas Emissions from Amazonian Hydroelectric Reservoirs: The Example of Brazil's Tucuruí Dam as Compared to Fossil Fuel Alternatives,' *Environmental Conservation* 24:1.
- Fearnside, P.M. (2002) 'Greenhouse Gas Emissions from a Hydroelectric Reservoir (Brazil's Tucuruí Dam) and the Energy Policy Implications,' *Water, Air, and Soil Pollution* 133:1.
- Fearnside, P.M. (2004a) 'Greenhouse Gas Emissions from Hydroelectric Dams: Controversies Provide a Springboard for Rethinking a Supposedly "Clean" Energy Source: An Editorial Comment,' *Climatic Change* 66:1,2.
- Fearnside, P.M. (2004b) 'Hydroelectric dams in Amazonia as contributors to global warming: The controversy heats up,' *Anais: III Conferência Científica do LBA Experimento de Grande Escala da Biosfera-Atmosfera na Amazônia*, 27 a 29 de julho de 2004, Academia de Tênis Resort, Brasília-DF, Brasil, p.88.
- Fearnside, P.M. (2005a) 'Brazil's Samuel Dam: Lessons for Hydroelectric Development Policy and the Environment in Amazonia,' *Environmental Management* 35:1.
- Fearnside, P.M. (2005b) 'Do Hydroelectric Dams Mitigate Global Warming? The Case of Brazil's Curuá-Una Dam,' *Mitigation and Adaptation Strategies for Global Change* 10: 675-691.
- Fearnside, P.M. (2006) 'Greenhouse Gas Emissions from Hydroelectric Dams: Reply to Rosa et al.,' *Climatic Change* 75:1-2.
- Frankignoulle, M. (1998) 'Carbon Dioxide Emissions from European Estuaries,' *Science* 282.
- Gagnon, L. (2002) 'The International Rivers Network statement on GHG emissions from reservoirs, a case of misleading science,' International Hydropower Association, London.
- Galy-Lacaux, G. et al. (1999) 'Long-term Greenhouse Gas Emissions from Hydroelectric Reservoirs in Tropical Forest Regions,' *Global Biogeochemical Cycles* 13:2.
- Gibbins, J. (2005) 'Carbon Capture & Storage,' presentation at Cambridge Energy Forum, 26 October.

IEA Implementing Agreement for Hydropower (2000) 'Hydropower and the Environment: Present Context and Guidelines for Future Action.'

International Hydropower Association (undated) 'Greenhouse Gas Emissions from Reservoirs.'

Kelly, C.A. et al. (1994) 'Turning Attention to Reservoir Surfaces, a Neglected Area in Greenhouse Studies', *EOS Trans. Am. Geophys. Union* 75.

Kemenes, A. et al. (2006) 'Gas Release Below Balbina Dam.' In *Proceedings of International Conference on Southern Hemisphere Meteorology and Oceanography (ICSHMO)*, Foz do Iguaçu.

Lambert, M. and Fréchet, J.-L. (2005) 'Analytical Techniques for Measuring Fluxes of CO<sub>2</sub> and CH<sub>4</sub> from Hydroelectric Reservoirs and Natural Water Bodies.' In Tremblay et al.

Matthews, C.J.D (2005) 'Carbon Dioxide and Methane Production in Small Reservoirs Flooding Upland Boreal Forest,' *Ecosystems* 8: 267–285.

Houel et al. (2006) 'Translocation of soil organic matter following reservoir impoundment in boreal systems: Implications for in situ productivity.' *Limnology and Oceanography* 51:3.

McCully, P. (2001) *Silenced Rivers: The Ecology and Politics of Large Dams*. Zed Books, London (updated and revised edition).

McCully, P. (2002) *Flooding the Land, Warming the Earth: Greenhouse Gas Emissions from Dams*. IRN, Berkeley.

Meier, P.J. (2002) 'Life Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis.' Fusion Technology Institute, University of Wisconsin, Madison.

Ministère de l'Économie (2002) 'Programmation pluriannuelle des investissements de production électrique.' Paris, p.71.

Ministério da Ciência e Tecnologia (2004) 'Brazilian Inventory of Anthropogenic Emissions by Sources and Removals by Sinks of Greenhouse Gases not Controlled by the Montreal Protocol.'

Pacca, S. (2003) 'Global Warming Effect Applied to Electricity Generation Techniques.' Dissertation in the Graduate Division, University of California, Berkeley.

Parekh, P. (2004) 'A Preliminary Analysis of the Impact of Dam Reservoirs on Carbon Cycling', prepared for International Rivers Network.

Raphals, P. (2001) *Restructured Rivers: Hydropower in the Era of Competitive Markets*. Helios Centre/International Rivers Network, Montreal/Berkeley.

Richard, S. et al. (2005) 'Impact of biomass decomposing during first years after dam construction: example of Petit Saut (French Guiana).' In dos Santos and Rosa (eds.).

Rosa, L.P. and R. Schaeffer (1994) 'Greenhouse gas emissions from power-dams', *Ambio* 23:2.

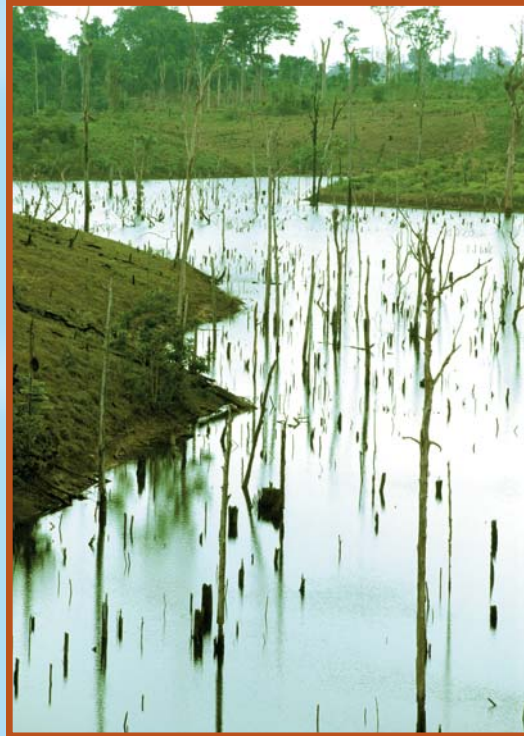
Rosa, L.P. and Santos, M.A. (2000) 'Certainty and Uncertainty in the Science of Greenhouse Gas Emissions from Hydroelectric Reservoirs.' World Commission on Dams Thematic Review II.2 Dams and Global Change, Cape Town.

Rosa, L.P. et al. (2002) 'First Brazilian Inventory of Anthropogenic Greenhouse Gas Emissions. Background Reports. Carbon Dioxide and Methane Emissions from Brazilian Hydroelectric Reservoirs,' Ministry of Science and Technology, Brasília, Annex B.

Rosa, L.P. et al. (2002?) 'Greenhouse Gases Emissions in Tropical Regions: Comments on the International Rivers Network Report,' COPPE/UFRJ.

- Rosa, L.P. et al. (2004) 'Greenhouse Gas Emissions from Hydroelectric Reservoirs in Tropical Regions,' *Climatic Change* 66:1-2.
- Rosa, L.P. et al. (2006) 'Scientific Errors in the Fearnside Comments on Greenhouse Gas Emissions (GHG) from Hydroelectric Dams and Response to His Political Claiming,' *Climatic Change* 75:1-2.
- Rudd, J.W.M. et al. (1993) 'Are Hydroelectric Reservoirs Significant Sources of Greenhouse Gases?' *Ambio* 22:4.
- Santos, M.A. (2000) 'Inventário de Emissões de Gases de Efeito Estufa Derivadas de Hidrelétricas.' Ph.D Thesis, UFRJ.
- Santos, M.A. et al. (2006) 'Gross greenhouse gas fluxes from hydro-power reservoirs compared to thermo-power plants,' *Energy Policy* 34:4.
- Santos, M.A. and L.P. Rosa (eds.) (2005) *Global Warming and Hydroelectric Reservoirs*. COPPE/UFRJ-Eletróbrás, Rio de Janeiro.
- Sikar, E. et al. (2005) 'Greenhouse Gases and Initial Findings on the Carbon Circulation in Two Reservoirs and their Watersheds,' *Verh. Internat. Verein. Limnol* 27.
- Soumis, N. et al. (2004) 'Greenhouse Gas Emissions from Reservoirs of the Western United States,' *Global Biogeochemical Cycles* 18.
- Soumis, N. et al. (2005) 'Hydroelectric Reservoirs as Anthropogenic Sources of Greenhouse Gases,' *Encyclopedia of Water*. John Wiley & Sons, Ohio.
- Spath, P.L. et al. (1999) 'Life Cycle Assessment of Coal-fired Power Production.' NREL, Colorado.
- Spath, P.L. and M.K. Mann (2000) 'Life Cycle Assessment of a Natural Gas Combined-Cycle Power Generation System.' NREL, Colorado.
- Svensson, B. (2005) 'Greenhouse gas emissions from hydroelectric reservoirs: A global perspective.' In dos Santos and Rosa (eds.).
- St. Louis, V.L. et al. (2000) 'Reservoir Surfaces as Sources of Greenhouse Gases to the Atmosphere: A global estimate,' *BioScience* 50:9.
- Therrien, J. et al. (2005) 'CO<sub>2</sub> Emissions from Semi-Arid Reservoirs and Natural Aquatic Ecosystems.' In Tremblay et al.
- Tremblay, A. et al. (eds.) (2005a) *Greenhouse Gas Emissions – Fluxes and Processes. Hydroelectric Reservoirs and Natural Environments*. Springer, Berlin.
- Tremblay et al. (2005b) 'GHG Emissions from Boreal Reservoirs and Natural Aquatic Ecosystems.' In Tremblay et al.
- Tremblay, A., et al. (2005c) 'Synthesis.' In Tremblay et al., p.638-657.
- Tremblay, A., M. Lambert and C. Demers (2005) 'Introduction'. In Tremblay et al. (eds.), p.21.
- Tremblay, A. and R. Schetagne (2006) 'The relationship between water quality and GHG emissions in reservoirs.' *Hydropower and Dams*, Issue One.
- World Commission on Dams (2000a) 'Dam Reservoirs and Greenhouse Gases: Report on the Workshop held on February 24 & 25. Hydro-Quebec, Montreal. Final Minutes.'
- World Commission on Dams (2000b) *Dams and Development: A New Framework for Decision-Making*. Earthscan, London.
- World Energy Council (2004) 'Comparison of Energy Systems using Life Cycle Assessment.'





**IRN**

**International Rivers Network**  
Linking Human Rights and Environmental Protection