The text that follows is a PREPRINT.

Please cite as:

Fearnside, P.M. & S. Pueyo. 2012. Underestimating greenhouse-gas emissions from tropical dams. *Nature Climate Change* **2**: 382–384.

Commentary
Underestimating greenhouse-gas emissions from tropical dams

Philip M. Fearnside[1] & Salvador Pueyo[2]

[1]National Institute for Research in Amazonia (INPA), C.P. 478, 69.011-970 Manaus, Amazonas, Brazil. [2]Institut Català de Ciències del Clima (IC3), C/ Doctor Trueta 203, 08005 Barcelona, Catalonia, Spain.

Emissions from tropical hydropower are often underestimated and can exceed those of fossil fuel for decades.

Tropical hydroelectric dams, such as those in Amazonia, emit significant amounts of greenhouse gases, especially methane[1-4]. These emissions have been underestimated or ignored in many global and national greenhouse-gas accounts. If any justification is given for omitting all or part of these emissions, it is usually that they are "controversial", "uncertain" or with "no consensus" (*e.g.,* 5, p. 84). However, while uncertainty regarding the quantities emitted is substantial[6], dam emissions need to be included in all accounting based on the best available data and calculation methods. Much of the wide variation in the emissions ascribed to tropical dams stems from omissions and errors in accounting, rather than from the physical measurements (which also subject to methodological problems). The fact that substantial emissions are involved can hardly be considered "uncertain", having been measured directly at reservoirs such as Balbina in Brazil[2] and Petit Saut in French Guiana[1]. Dam emissions are of two types: reservoir surface or "upstream" emissions and emissions from the water that passes through the turbines and spillways ("degassing" or "downstream" emissions). Where dam emissions are counted, they often include only the upstream emissions, as in estimates by ELETROBRÁS[7]. The recent IPCC special report on renewable energy reviews life-cycle assessments for various technologies, and for the typical case (*i.e.*, the 50th percentile), ranks hydro as having half or less impact as compared to any other source, including solar, wind and ocean energy (5, p. 982). The basis in data used for this optimistic classification is unclear from the report.

Carbon that is emitted as CO_2 can come from two types of sources: 1) fixed sources that produce a one-time emission, such as the trees killed by flooding the reservoir and the stocks of carbon in the soil (Fig. 1), and 2) renewable sources such as carbon that is removed from the atmosphere through photosynthesis by macrophytes (water weeds), phytoplankton or algae in the reservoir, trees in the watershed that produce litter that is washed into the reservoir by rainwater, or vegetation in the drawdown zone (the area that is temporarily exposed each time the water level is lowered in the reservoir). CO_2 from fixed sources must be counted as contributions to global warming, especially decay of dead trees that are left projecting out of the water in Amazonian reservoirs (but they have often been omitted). By contrast, CO_2 from the renewable sources is not a net emission, as this CO_2 is exactly balanced by the carbon removed from the atmosphere when the biomass is formed (which has not been included in the accounting). All of the methane emission, on the other hand, makes a net contribution to global warming. The reservoir's function in transforming renewable carbon into methane gives it the role of a "methane factory", continuously removing carbon from the atmosphere as CO_2 and returning it as CH_4, with a much greater impact on global warming[8]. Methane is formed where organic matter decays under anoxic conditions, as in the sediments at the bottom of a reservoir. The soft vegetation that grows when the drawdown zone is exposed will decay under anoxic conditions on the bottom of the reservoir, releasing methane.

The water in a tropical reservoir stratifies thermally, with a warm layer (epilimnion) in the upper 2-10 m where the water is in contact with the air and contains oxygen, and a colder layer (hypolimnion) at the bottom where any oxygen is quickly exhausted and virtually all decay produces methane rather than CO_2. Water passing through the turbines and spillways is drawn from the lower layer (Fig. 2). Downstream emissions occur as the water is released under pressure below the dam. Just as bubbles emerge upon opening a bottle of a soft drink, the release of pressure reduces the solubility of gases, causing bubbles to form (Henry's law)[9]. Later, warming of water in the river below the dam causes further release. Downstream emissions have been omitted in a number of global compilations of estimates of dam impacts, such as those led by St Louis[10], Batsviken[11] and Barros[12]. The proportion of upstream and downstream methane emission depend on the area of the reservoir and the magnitude of the river's flow: upstream emission is proportional to the reservoir area but downstream emission is proportional to streamflow. At Brazil's Balbina, where the reservoir area is unusually large (approximately 3000 km^2) and the average streamflow unusually small (657 m^3/s), about half (53%) of the methane emission is downstream[13]. At Tucuruí, with approximately the same reservoir area as Balbina but 17 times more streamflow, downstream emissions represent 88-93% of the CH_4 (3, p. 85).

When downstream emissions have been included, they have often been underestimated by methods that miss a major portion of the release. Because much of the methane is released immediately as the water emerges from the turbines, and even inside the turbines themselves, estimates based on flux measurements by samplers floating on the water surface in the river some distance downstream (*e.g.,* 14) will inevitably miss much of this emission. The only practical means of avoiding this bias is to calculate the immediate "degassing" emission from the difference in CH_4 concentration in the water in the reservoir at the turbine intake depth and in the water below the dam (*e.g.,* 8).

A methodological factor that affects all of the concentration-based estimates so far essentially doubles the methane emission from water passing through the spillways and turbines in typical Amazonian dams. The effect is depth dependent: CH_4 concentration in the water at the turbine level (normally near the bottom of the reservoir) is critical, and this has traditionally been measured in water that is brought to the surface in a Ruttner bottle, from which a sample is drawn with a syringe and analyzed chemically. Any methane that comes out of solution as the bottle is raised to the surface is lost. A sampling device dubbed the "Kemenes bottle" captures and measures this methane, yielding concentration values for CH_4 at a typical turbine depth of 30 m that are approximately double those of measurements using Ruttner bottles; in the case of Balbina, this results in an average turbine degassing emission calculated from concentration difference (using Kemenes bottles) that is 116% higher than the average based on simultaneous sampling with Ruttner bottles[2].

The importance of emissions released immediately at the turbine outlet is illustrated by the results at Balbina[2]. In this case, the dam's turbine intake includes a funnel-like structure that draws water from 14 to 30 m depth. Considering the CH_4 concentration integrated over the full hypolimnion, the amount released downstream (by immediate bubbling at the turbines plus by diffusion in the river further downstream) would be 2.2 times greater than the downstream diffusion emission alone if the immediate release is based on Ruttner bottle samples, or 3.4 times more if based on Kemenes bottle samples. If the calculation is based on the location of the turbine intake sill at 30-m depth, the corresponding multipliers would be 7.8 and 15.6, respectively. In other words, estimates of downstream

emissions based only on fluxes captured by surface chambers in the river below the dam report less than half and possibly as little as one-sixteenth of the actual downstream emission.

Various mathematical errors have resulted in Brazil's electrical authorities estimating the magnitude of emissions from reservoir surfaces at a level only one-fourth what it should be (see detailed explanation in ref. 15). ELETROBRÁS[7] calculated the surface emissions of CH_4 bubbling for each of Brazil's 217 large dams in 2000 by applying a power-law correction to a mean of measured values (in $g/m^2/d$) for seven reservoirs. The power law is used to capture the effect of infrequent but large events. For example, in the case of earthquakes many small quakes and only a few major ones occur. By using information on the frequency of quakes measured at different magnitudes, one can calculate the frequency of much larger quakes that are inevitably underrepresented in the available data. The same applies to methane emissions from a reservoir surface, where most measurements will record only a modest emission but a small number of very large emission events do occur. In other words, correcting for these rare events with the power law will inevitably increase the emission estimate above the simple average of a set of measurements. However, the ELETROBRÁS calculation contains no less than five mathematical errors, including a change of sign from positive to negative[15]. The ELETROBRÁS calculation reduces the reservoir surface estimate by 76% below the simple arithmetic mean, whereas a correct application of the power law to the same data would make the corrected estimate 345% higher than the ELETROBRÁS estimate[15]. Brazil's hydroelectric reservoirs in 2000 totaled $33 \times 10^3 \, km^2$, an area larger than Belgium. The difference between the ELETROBRÁS estimate of methane emission from this surface (0.22×10^6 Mg/year) and our correction of the calculation (0.98×10^6 Mg/year) is equivalent to 7.0×10^6 Mg of CO_2-equivalent carbon per year, or an emission approximately equal to that of greater São Paulo[15] if calculated using a global warming potential (GWP) of 34 over a 100-year time horizon[16]. The magnitude of the underestimation in the ELETROBRÁS calculation would be equivalent to 5.2×10^6 Mg of CO_2-equivalent carbon if one uses the lower GWP of 25 now adopted by the Climate Convention for the 2013-2017 period but which omits indirect effects of methane.

The Brazilian Ministry of Mines and Energy's ten-year plan covering the 2011-2020 period calls for construction of an additional 48 large dams, 30 of which would be in the country's Legal Amazon region (17, p. 285). This means building one dam every four months in Amazonia. Dam building is shifting to tropical areas on a global scale, including ELETROBRÁS plans to build over a dozen dams in Peru and other Amazonian countries. Tropical dams (the subject of the present commentary) emit more greenhouse gases than do dams in other zones (*e.g.*, 12, 18).

Amazonia dams are being promoted, in part, on the basis of a supposed benefit in mitigating global warming (19, pp. 32-33), including the intention of capturing mitigation funds on a large scale under the Kyoto Protocol's Clean Development Mechanism (19, p. 118). Unfortunately, these dams can be expected to have cumulative emissions that exceed those of fossil-fuel generation for periods that can extend for several decades, making them indefensible on the basis of global-warming mitigation[20.] In the case of Brazil, much of the country's Amazon forest is under risk from the consequences of global warming on this time scale[21]. The time frame is critical in dealing with global warming: dams produce a large emission in the first few years followed by a lower emission that is sustained indefinitely, while generation from fossil fuels produces emissions at a constant rate[22]. The greenhouse gas "debt" created by the dam in the first years when emissions are much higher than those from fossil-fuel generation can take decades to pay off after the dam emissions stabilize at a

level below those of fossil fuels[4]. The consequences are grave of waiting decades to begin effective reduction of global emissions.

Controlling global warming will require mitigation measures that are sufficient to keep the atmospheric concentration of greenhouse gases below a level defined as "dangerous". All emissions must be mitigated, whether or not they are the result of deliberate human actions like building dams and whether or not their reporting is currently mandatory under Climate-Convention guidelines. If any of these emissions are ignored or understated, then the national quotas (assigned amounts) negotiated to reduce emissions will be insufficient, and global temperatures will continue to increase, along with all of the impacts that this implies. Among the issues to be faced is counting all emissions from dams and including them in national inventories. The emissions from tropical hydropower mean that this is not "clean" energy and that countries need to commit to making deeper cuts in their anthropogenic greenhouse gas emissions than they have been willing to consider so far.

1. Abril, G. *et al*. *Global Biogeochem. Cycles* **19**, GB 4007, doi: 10.1029/2005GB002457 (2005).

2. Kemenes, A., Forsberg, B. R. & Melack, J. M. *Jour. Geophys. Res.* **116**, G03004, doi: 10.1029/2010JG001465 (2011).

3. Fearnside, P. M. *Water, Air and Soil Poll.* **133**, 69-96 (2002).

4. Fearnside, P. M. *Novos Cadernos NAEA* **12**(2), 5-56 (2009). [English translation available at: http://philip.inpa.gov.br/publ_livres/mss%20and%20in%20press/Belo%20Monte%20emissions-Engl.pdf]

5. IPCC (Intergovernmental Panel on Climate Change). *Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change*. (eds. Edenhofer, O. *et al.*), (Cambridge University Press, Cambridge, UK, 2012).

6. Demarty, M. & Bastien, J. *Energy Policy* **39**, 4197-4206 (2011).

7. Brazil, ELETROBRÁS (Centrais Elétricas Brasileiras S/A). *Emissões de dióxido de carbono e de metano pelos reservatórios hidrelétricos brasileiros: Relatório final. Relatório Técnico*. (ELETROBRÁS, Rio de Janeiro, RJ, Brazil, 2000).

8. Fearnside, P. M. *Oecologia Brasiliensis* **12**, 100-115 (2008). [English translation available at: http://philip.inpa.gov.br/publ_livres/mss%20and%20in%20press/Fearnside%20Hydro%20GHG%20framework.pdf]

9. Fearnside, P. M. *Climatic Change* **66,** 1-8. doi: 10.1023/B:CLIM.0000043174.02841.23 (2004).

10. Saint Louis, V. C., Kelly, C., Duchemin, E., Rudd, J. W. M. & Rosenberg, D. M. *Bioscience* **20,** 766 (2002).

11. Bastviken, D., Tranvik, L. J., Downing, J. A., Crill, P. M. & Enrich-Prast, A. *Science* **331**, 50 (2011).

12. Barros, N. *et al*. *Nature Geosci.* **4**, 593–596. doi: 10.1038/NGEO1211 (2011).

13. Kemenes, A., Forsberg, B. R. & Melack, J. M. *Geophys. Res. Lett.* **34**, L12809. doi: 10.1029/2007GL029479.55 (2007).

14. dos Santos, M. A. *et al*. *Oecologia Brasiliensis* **12**, 116-129 (2008).

15. Pueyo, S. & Fearnside, P. M. *Oecologia Australis* **15**, 114-127, doi: 10.4257/oeco.2011.1502.02 (2011). [English translation available at: http://philip.inpa.gov.br/publ_livres/mss%20and%20in%20press/Pueyo%20&%20Fearnside-GHGs%20FROM%20%20RESERVOIRS--engl.pdf]

16. Shindell, D. T. *et al*. *Science* **326**, 716-718 (2009).

17. Brazil, MME (Ministério de Minas e Energia). *Plano Decenal de Expansão de Energia 2020.* (MME, Empresa de Pesquisa Energética, Brasília, DF, Brazil, 2011).

18. Del Sontro, T. *et al*. *Environ. Sci. and Technol.* **44**, 241-2425. doi**:** 10.1021/es9031369 (2010).

19. Brazil, CIMC (Comitê Interministerial sobre Mudança do Clima). *Plano Nacional sobre Mudança do Clima – PNMC -- Brasil.* (Ministério do Meio Ambiente, 2008).

20. Fearnside, P. M. *Mitigat. and Adaptat. Strat. for Global Change* (in press) doi: 10.1007/s11027-012-9382-6 (2012).

21. Fearnside, P. M. *Oecologia Australis* **13**, 609-618. doi: 10.4257/oeco.2009.1304.05 (2009).

22. Fearnside, P. M. *Environ. Conserv.* **24**, 64-75. doi:10.1017/S0376892997000118 (1997).

23. Rosa, L. P., dos Santos, M. A., Tundisi, J. G. & Sikar, B. M. in *Hydropower Plants and Greenhouse Gas Emissions* (eds. Rosa, L. P. & dos Santos, M. A.) 41-55 (Coordenação dos Programas de Pós-Graduação em Engenharia (COPPE), Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil,1997).

FIGURE LEGENDS

Fig. 1 – Dead trees in Brazil's Samuel reservoir. Above-water decay of this fixed carbon source releases CO_2.

Fig. 2 – Methane-rich water is drawn from below the thermocline that divides the water column into a surface layer (epilimnion) and an anoxic bottom layer (hypolimnion). The thermocline prevents cold water at the bottom of the reservoir from reaching the surface. A schematic of Brazil's Tucuruí Dam (right) shows spillway and turbine depths at the time of a 1989 measurement of methane concentrations by José Tundisi (left; data in 23). The water

level has been raised by an additional 2 m since 2002. The release of pressure as the water emerges allows the methane to "degas" to the atmosphere.