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Emissions from tropical hydropower and the IPCC

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ABSTRACT

Tropical hydroelectric emissions are undercounted in national inventories of greenhouse gases under the United Nations Framework Convention on Climate Change (UNFCCC), giving them a role in undermining the effectiveness of as-yet undecided emission limits. These emissions are also largely left out of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Renewable Energy Sources and Climate Change Mitigation, and have been excluded from a revision of the IPCC guidelines on wetlands. The role of hydroelectric dams in emissions inventories and in mitigation has been systematically ignored.

1. Emissions from tropical dams

Amazonian dams produce greenhouse gases, especially during their first 10 years of operation (e.g., Abril et al., 2005; Delmas et al., 2005; Fearnside, 2002a, 2005a, 2008a, 2009, 2013; Fearnside and Pueyo, 2012; Galy-Lacaux et al., 1997, 1999; Guérin et al., 2006; Gunkel, 2009; Kemenes et al., 2007, 2008, 2011; Pueyo and Fearnside, 2011). Published numbers for emissions from hydroelectric dams vary widely, but most of this variation can be explained by known differences between the dams in question and by known omissions and problems in measurement methodology, particularly for the low values. The existence of uncertainty has been used repeatedly as a justification for not taking hydropower emissions into account. Among the examples of this practice is the current set of Intergovernmental Panel on Climate Change (IPCC) guidelines for national inventories, which opted not to provide default values for the major hydropower emissions sources from degassing at turbines, from ebullition (bubbling) from the reservoir surface, and from both ebullition and diffusion in the river downstream of the dam (IPCC, 2006, vol. 4, Appendix 3).

2. Dams in IPCC reports and guidelines

2.1. Special report on renewable energy

The IPCC special report on renewable energy sources and climate change mitigation (IPCC, 2012) summarized its findings on emissions from hydroelectric dams as: "there is currently no consensus on whether reservoirs are net emitters or net sinks" (Arvizu et al., 2012, p. 84). The report classified hydropower as having half or less impact per kWh of electricity generated as compared to any other source, including wind and solar (Moomaw et al., 2012, p. 982) (Fig. 1). One factor that may, in part, explain the report's conclusion that hydropower has such low emissions is the preponderance of temperate and boreal locations among existing dams. Although the summary table indicates that three values were used from tropical dams, none of the 11 sources used in the study from all climatic zones (Moomaw et al., 2012, p. 986) appears to concern tropical dams (Table 1). Only one source listed concerns Brazil (Ribeiro and da Silva, 2010). This is a life-cycle analysis of the Itaipu Dam (Fig. 2), which is located on the border between Brazil and Paraguay (not a tropical dam); the greenhouse-gas estimates

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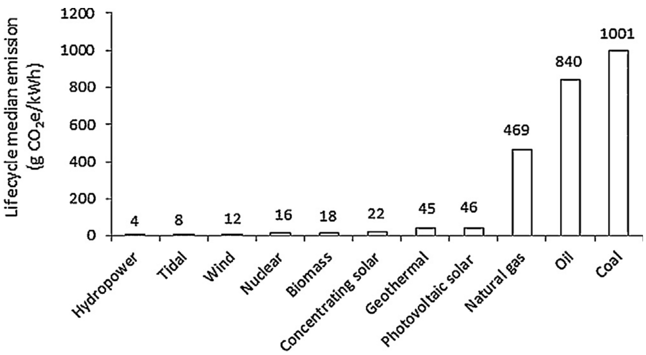

Fig. 1 – Lifecycle median emissions of different sources of electricity according to the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (data for 50% percentile from Moomaw et al., 2012, p. 982).

used in the Itaipu study are from official numbers that omit emission from the turbines and that underestimate reservoir surface emissions by a factor of three due to mathematical errors (Pueyo and Fearnside, 2011; see also Fearnside and Pueyo, 2012). Only four of the 11 sources used in the IPCC special report are from published peer-reviewed literature (Table 1).

The literature used by the special report is so reduced because the selection procedure that was adopted restricted consideration to dams where emissions had been reported that were "easily convertible to the functional unit chosen for this study: grams of CO_2e per kWh generated" (Moomaw et al., 2012, p. 981) (see also critique by CO2list, 2011, which also lists numerous omissions in the few studies that were used in the special report's global estimates). "CO_2e," or "carbon-dioxide equivalents," expresses the impacts on global warming of all gases, including methane (CH_4) and nitrous oxide (N_2O), in terms of the weights of CO_2 that would have the same effect based on the global warming potential (GWP) of each gas (see Section 3.6). One emissions source explicitly excluded by the IPCC authors was land-use change (Moomaw et al., 2012, p. 981); dams in tropical forest areas often provoke deforestation with significant emissions (e.g., Barreto et al., 2011). The results also had to fit into a life-cycle analysis, and these were used in the special report "as published" without any standardization or accuracy assessment for studies that passed the screening criteria (Moomaw et al., 2012, p. 980). Most of the 11 studies of hydroelectric dams assumed a lifespan of 100 years, a factor that weighs heavily in favor of hydropower in calculations such as these with no discounting for time (see Section 3.7). Note that life-cycle analyses are often incomplete, with different emissions sources being omitted in individual studies (Table 1). For inclusion in the report the studies had to include at least two phases of the life cycle, but could omit other phases without any adjustments for these omissions (Moomaw et al., 2012, p. 980). One phase often omitted is decommissioning of a dam at the end of its useful life. Justifications for this reveal the selective nature of choices regarding the value of time: the virtually universal choice of the hydroelectric industry is to give no value to time, considering an emission of a ton of carbon in the first year, for example, to have the same value as a ton emitted a century in the future (see Section 3.7). But in the case of decommissioning the opposite argument is used: for example, the study by Denholm and Kulcinski (2004, p. 2158) used in the IPCC special report states that "Although not considered in this assessment, the energy and emissions related to decommissioning can potentially be discounted due to their impacts at a future date."

Although the special report is dominated by non-tropical dams, the current expansion of hydropower focuses on tropical regions such as Amazonia where dams emit much larger amounts of greenhouse gases than in temperate and boreal locations. Important exceptions to the tropics as the location of current dam building are China and high-elevation sites in the Himalayas and Andes. Dams in the humid tropics dominate in Brazil, where the country's 2013–2022 10-year energy expansion plan calls for 18 "large" dams by 2022 in the country's Legal Amazon region (Brazil, MME, 2013). In Brazil "large" dams are those with over 30 MW of installed capacity.

Tropical dams, especially those in the wet tropics, emit substantially more greenhouse gases than do those in other climatic zones (see extensive review by Barros et al., 2011). This is reflected in life-cycle studies: a review by Steinhurst et al. (2012) concludes that tropical dams emit 1300–3000 g CO_2e/kWh, versus 160–250 g CO_2e/kWh for boreal dams, with thermoelectric plants using natural gas, oil and coal emitting 400–500, 790–900 and 900–1200 g CO_2e/kWh, respectively.

As an illustration, emissions can be calculated for the Petit Saut Dam in French Guiana, which is the best-studied tropical dam for greenhouse gas emissions. A 20-year calculation is given in Table 2, including a comparison with production of the same amount of electricity from a combined-cycle natural gas plant. The 20-year period is the relevant time frame for maintaining mean global temperature from passing the limit of 2 °C above the pre-industrial mean (see Section 3.7). The comparison indicates 22 times more emission (g CO_2e/kWh) from the dam as compared to natural gas based on a 20-year GWP for converting methane to CO_2e (see Section 3.6). Even if the 100-year GWP is used the dam has 19 times more emission in the first 20 years.

Two components of the Petit Saut Dam's net impact are omitted in the calculation in Table 2: avoided emissions from the soil under the natural forest that is lost to flooding and emission from the soil in the drawdown zone. Petit Saut has a 100-km^2 drawdown zone (Abril et al., 2005, p. 4), or 18% of the 560-km^2 area of original forest that was flooded. The drawdown zone is exposed each year when the water level in the reservoir is lowered and has wet soil that can be expected to emit methane during part of the year. In contrast, well-drained soils under humid tropical forests are usually methane sinks rather than sources (22 studies reviewed by Potter et al., 1996 have a mean uptake of 3.8 kg CH_4/ha/year). Some ponding occurs during the rainy season in *terra firme* (unflooded upland) tropical forests, but the percentage of the total area is not large: in forests near Manaus, Brazil, these areas represent 5% of the area per flooding event (Mori and Becker, 1991); however, flooding events only occur once every few years. Delmas et al. (2001) give a high estimate for avoided

Table 1 – Papers on hydroelectric dam emissions used in the IPCC special report.

No.	Reference	Locations of dams	Names of dams	Emissions included								Total g CO_2e/kWh	Notes
				Construction materials and energy	Vegetation & soil carbon loss	Operation materials and energy	Reservoir surface	Degassing at turbines & spillways	Downstream river	Decomissioning materials and energy	Sediment carbon release after decomissioning		
1	Barnthouse et al. (1994)	U.S.A.: Washington state	Rocky Creek, Diobsud Creek, Boulder Creek, Jordan Creek, Irene Creek, Jackman Creek	x		x						8.7	(a)
2	Denholm and Kulcinski (2004)	U.S.A.: South Carolina, California, Virginia, Missouri, Colorado, Georgia, Tennessee	Bad Creek, Balsam Meadow, Clarence, Fairfield, Helms, Mt. Elbert, Raccoon Mtn., Rocky Mtn.	x		x						5.6	(b)
3	Dones et al. (2005)	Switzerland	Data materials and energy data from "more than 50 Swiss reservoir power plants"	x	x	x	x			x		3.77	(c)
4	Dones et al. (2007)	Switzerland	Data materials and energy data from "more than 50 Swiss reservoir power plants"	x	x	x	x			x		3.77	(d)
5	Horvath (2005)	U.S.A.: Arizona	Glen Canyon		x						X	35	(e)
6	IEA (1998)	No data on specific dams.											
7	Pacca (2007)	U.S.A.: Arizona, Nevada, North Dakota, South Dakota, Montana	Hoover, Glen Canyon, Garrison, Oahe, Fort Peck, Fort Randall								X	35-380	(f)

Table 1 (*Continued*)

No.	Reference	Locations of dams	Names of dams	Emissions included								Total g CO_2e/kWh	Notes
				Construction materials and energy	Vegetation & soil carbon loss	Operation materials and energy	Reservoir surface	Degassing at turbines & spillways	Downstream river	Decomissioning materials and energy	Sediment carbon release after decomissioning		
8	Rhodes et al. (2000)	U.S.A.: Washington State	Chelan	x		x						1.592	(g)
9	Ribeiro and da Silva (2010)	Brazil/ Paraguay	Itaipu	x		x	x					4.86	(h)
10	Vattenfall (2008)	Sweden	Seitevare, Harsprånget, Porsi, Boden, Juktan, Umluspen, Stornorrfors, Stalon, Bergeforsen, Älvkarleby, Olidan, Hojum, Pamilo, Upperud	x	x	x						4.5	(i)
11	Zhang et al. (2007)	China	Based on ‘‘nominally confidential’’ reports on two projects, denominated ‘‘A’’ and ‘‘B’’.	x		x						25.05	(j)

(a) Projects are for diversion canals added to planned small dams (dam constuction emissions not included).
(b) Pumped hydro storage (PHS) dams. Emissions of individual gases and GWPs used for conversions are not given.
(c) Earlier version of estimates in Dones et al. (2007).
(d) Reservoir emissions ‘‘assumed for general alpine conditions’’ estimated ‘‘using limited information available on Swiss natural lakes’’ (Dones et al., 2007, p. 10). Emissions for Swiss storage dams are 4.0 gCO_2e/kWh (54% of total hydropower production) and 3.5 gCO_2e/kWh for run-of-river plants (46%). Publication extrapolates from Swiss dams to estimate emissions for reservoir plants in alpine areas in the rest of Europe (4.5 g CO_2e/kWh), European non-alpine areas (10.0 g CO_2e/kWh), and Finland (34.0 gCO_2e/kWh), and for run-of-river plants in the rest of Europe (3.5 gCO_2e/kWh). GWPs are 100-year values from the IPCC 3rd assessment report.
(e) This unreviewed working paper appears to contain mathematical errors in converting CH_4 to CO_2e; the GWP used is not given but is described as a 20-year GWP, but calculations are not reproducible with any IPCC values.
(f) Uses IPCC third assessment report 100-year GWPs.
(g) Uses IPCC first assessment report 100-year GWPs.
(h) Based on 100-year life, construction + operation releases 0.132 g CH_4 and 1.56 g CO_2/kWh, totaling 4.9 gCO_2e/kWh if calculated with IPCC fourth assessment report 100-year GWPs.
(i) The 2011 version of the report (not used by the IPCC) raises this estimate to 8.6 gCO_2e/kWh.
(j) Project ‘‘A’’ = 44 g CO_2e/kWh; Project ‘‘B’’ = 6.1 g CO_2e/kWh.

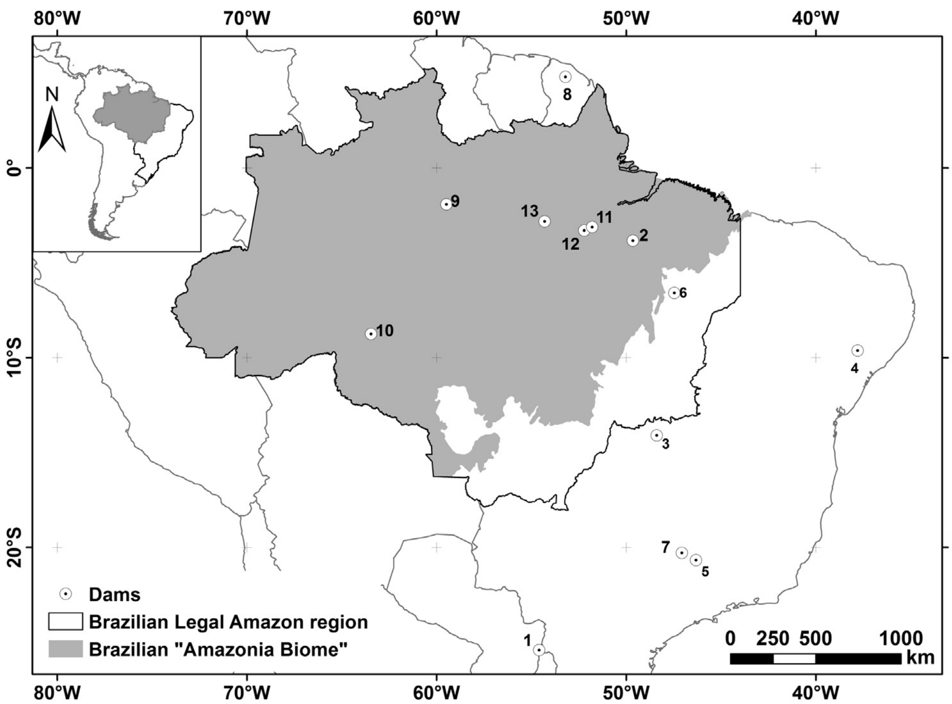

Fig. 2 – South American dams mentioned in the text: 1 = Itaipu, 2 = Tucuruí, 3 = Serra da Mesa, 4 = Xingó, 5 = Furnas, 6 = Estreito, 7 = Peixoto, 8 = Petit Saut, 9 = Balbina, 10 = Samuel, 11 = Belo Monte, 12 = Babaquara/Altamira, 13 = Curuá-Una. Brazil's "Legal Amazon region" and "Amazonia Biome" are also shown.

forest soil emissions; other estimates are much lower (e.g., Fearnside, 2009). The soil emission from the drawdown zone is believed to be larger than the avoided forest soil emission, making Table 2 conservative as an estimate of net impacts of Petit Saut.

2.2. *National inventories of greenhouse-gas emissions*

Emissions from tropical dams represent a significant lacuna in the national greenhouse-gas inventories compiled for the United Nations Framework Convention on Climate Change (UNFCCC). Reporting for each item under the IPCC guidelines can be done at one of three "tiers" or levels of methodological complexity. Tier 1 is the basic level, which is designed so that it can be applied by all countries, including those with little data or expertise; Tier 2 is an intermediate level that allows for higher-resolution country-specific emission factors; Tier 3 is the highest level and gives flexibility either for country-specific methods, including both modeling and direct measurements, or for a higher level of disaggregation. The revised IPCC 1996 guidelines that were in effect through 2014 for both Annex I and non-Annex I countries [i.e., countries with and without national emissions limits] omit reservoirs entirely (IPCC, 1997). The IPCC Good Practice Guidelines, which were in effect through 2014 as a supplement for Annex I countries, provide some information for voluntary reporting, but the portion on reservoirs (Appendix 3a.3) is titled as a mere "basis for future methodological development" (IPCC, 2003). This appendix states that "Due to the close linkage between CO_2, CH_4 and N_2O emissions and methodologies, all three gas species are addressed in this section and no distinction for emissions from flooded land is made based on the age of the reservoir" (IPCC, 2003, Appendix 3a.3, p. 3.286). This is strange given that the very large peak of methane emissions in the first years after creating a reservoir in the tropics had been known for at least a decade at the time and was documented in some of the papers cited in the report. No Tier 1 reporting is suggested, and the report suggests that countries can develop their own parameters if they wish to report at the Tier 2 or 3 levels (Ranges of published estimates are given for CH_4 diffusion and bubbling from tropical reservoir surfaces).

The IPCC produced a new set of guidelines in 2006, which provides information for reservoir emissions in an appendix. The 17th Conference of the Parties (COP-17) held in Durban in 2011 decided that the IPCC, 2006 guidelines for national inventories would be used beginning in 2015 for Annex I countries (Decision 15/CP.17: UNFCCC, 2012). For reporting of methane emissions the Tier 1 level is specified as only including the relatively modest emissions occurring by means of diffusion from the reservoir surface. Countries can opt to report bubble emissions from reservoir surfaces at the Tier 2 level, but the major emissions of methane from the turbines are only reported at the rarely used Tier 3 level (IPCC, 2006, vol. 4, Appendix 3). The appendix on reservoirs in the 2006 guidelines (IPCC, 2006, vol. 4, Appendix 3) is identified as an update of the IPCC Good Practice Guidelines (IPCC, 2003, Appendix 3a.3), but not all of the changes represent additions: the table of data on bubbling emissions disappeared (IPCC, 2003, Appendix 3a.3, p. 3.290, Table 2A.3.4 versus IPCC, 2006, vol. 4, Appendix 3, p. Ap.3.5, Table 2A.2). The key meeting in

Table 2 – Estimated emissions over 20 years for Petit Saut Dam in French Guiana and comparison with natural gas generation.

	CO_2		N_2O	CH_4		N_2O		Total CO_2e $CO_2 + CH_4 + N_2O$		20-year emission/kWh (b) $CO_2 + CH_4 + N_2O$	
								20-yr GWP (a)	100-yr GWP (a)	20-yr GWP (a)	100-yr GWP (a)
	(Gg CO_2)	(Gg CH_4)	(Gg N_2O)	(Gg CO_2e)	(Gg CO_2e)	(Gg CO_2e)	(Gg CO_2e)	(Gg CO_2e)	(Gg CO_2e)	(g CO_2e/kWh)	(g CO_2e/kWh)
Petit Saut Dam											
Construction (c)								277	277	36	36
Reservoir, degassing & downstream (d)	9675	693	9	59,598	23,562	2506	2515	69,273	33,237	9112	4372
Above-water decay of dead trees (e)	9814	220		18,920	7480			28,734	17,294	3780	2275
Total	19,489	913	9	78,518	31,042	2506	2515	98,285	50,809	12,928	6683
Combined-cycle natural gas											
Construction (c)	6.0							6.0	6.0	0.8	0.8
Operation (fuel combustion) (g)	1535.4	0.03	0.003	2.6	1.0	0.8	0.8	1538.7	1537.2	202.4	202.2
Gas production (h)		2.14		184.0	72.7			184.0	72.7	24.2	9.6
Gas processing, transport & distribution (i)		3.55		305.2	120.7			305.2	120.7	40.1	15.9
Fugitive emissions (CH_4 leakage)(j)		27.67		2,379.9	940.9			2,379.9	940.9	313.0	123.8
Total	1541.4	33.39	0.003	2871.7	1,135.3	0.8	0.8	4413.9	2677.5	580.6	352.2

(a) CH_4 20-yr GWP = 86; 100-yr GWP = 34; N_2O 20-yr GWP = 264; 100-yr GWP = 265 (Myhre et al., 2013, p. 714).
(b) Power production from 1994 to 2005 from ADEME Guyane (nd). Production from 2006 to 2013 assumed same as 2001–2005 mean (416 GWh/yr). Twenty-year total = 7602 GWh.
(c) Based on study of five proposed dams in Chile (Burrall et al., 2009); quantities are made proportional to Petit Saut (560 MW installed; 7602 GWh generated in 20 years).
(d) CH_4 from Delmas et al. (2005, p. 996); see also Delmas et al. (2001). Measurements extend through 2003 and trends are extrapolated by the authors for subsequent years. N_2O from Guérin et al. (2008).
(e) Based on estimate for Petit Saut for 100 years by Abril et al. (2013); here, 2/3 of the emission is assumed to occur in the first 20 years as a rough estimate based on Balbina after 23 years (see Abril et al., 2013).
(f) Gas consumption 561 Gg CH_4 or 30.1×10^6 GJ input in 20 years (see note i). Emission factor 15.3 tC/TJ (IPCC, 1997, vol. 1, p. 1.24), conversion factor 0.0036 MWh/TJ [1 kWh = 3.6 MJ], energy content of gas 53.6 MJ/kg (Australian Gas Networks, 2007), CH_4 emission factor for energy industries 1 kg CH_4/TJ input (IPCC, 1997, vol. 1, p. 1.35). N_2O emission factor 0.1 kg/TJ [g/GJ] (IPCC, 1997, vol. 1, p. 1.36). CO_2 from 0.995 fraction of oxidized C (IPCC, 1997, vol. 1, p. 1.8).
(g) Gas production needed to supply the plant is calculated at 589 Gg CH_4 in 20 years, based on consumption of 561 Gg CH_4, derived from 53.6 MJ/kg [TJ/Gg] energy content of gas (CH_4) (Australian Gas Networks, 2007), 0.995 fraction of C oxidized (IPCC, 1997, vol. 1, p. 1.8).
(h) Gas production needed to supply the plant is calculated at 589 Gg CH_4 in 20 years, based on consumption of 561 Gg CH_4, derived from 53.6 MJ/kg [TJ/Gg] energy content of gas (CH_4) (Australian Gas Networks, 2007), 0.995 fraction of C oxidized (IPCC, 1997, vol. 1, p. 1.8), efficiency of 57.5% (midpoint of Brazilian range of 55–60% (Correia Neto and Tolmasquim, 2001) and generation in 20 years of 27.4×10^9 GJ (1 kWh = 3.6 MJ). Emission factor for gas production: 288×10^3 kg CH_4/PJ gas produced (IPCC, 1997, vol. 1, p. 1.121).
(i) Emission factor 118×10^3 kg CH_4/PJ of gas consumed (IPCC, 1997, vol. 1, p. 1.121).
(j) Based on estimate of 4.7% leakage in Brazil from 1999 Petrobrás data (dos Santos et al., 2006, p. 486). The gas production to which this percentage is applied is calculated at 589 Gg CH_4 in 20 years, based on consumption of 561 Gg CH_4, derived from 53.6 MJ/kg [TJ/Gg] energy content of gas (CH_4) (Australian Gas Networks, 2007), 0.995 fraction of C oxidized (IPCC, 1997, vol. 1, p. 1.8), efficiency of 57.5% (Correia Neto and Tolmasquim, 2001) and generation in 20 years of 27.4×10^9 GJ (1 kWh = 3.6 MJ).

2005 that resulted in this section of the guidelines was described as follows by one of the participants: "Our last meeting (Sydney in last December) was very tough. Political Conclusion: CO_2 emissions should remain in the main body of the 2006 IPCC guidelines but CH_4 will be in an annex. . bubbles and degassing emissions are only considered, respectively, under Tier 2 and 3 approaches. The Hydro-Quebec expert argues that we don't have enough knowledge for CH_4 diffusive emissions. . .." (Duchemin, 2006).

The IPCC (2006) guidelines appendix ("annex") provides a default value for the diffusion flux of methane from tropical reservoir surfaces (IPCC, 2006, vol. 4, Appendix 3, p. Ap.3.5). This is calculated as the median value from a series of published measurements in different reservoirs. The median is used instead of the mean because the distribution of values is highly skewed. The median is often used instead of the mean as a way of minimizing the effect of outlier values that are the result of measurement errors. However, the skewed distribution of methane flux values is not the result of measurement error, but rather a feature of the system itself. On most days, the rate of emission will be modest, but less frequently there will be large bursts of emission. A similar situation applies to data from different reservoirs. Since the objective of the IPCC default value is for estimation of an annual total of emissions, the metric needed is best approximated not by the median but rather by the mean. Using a median effectively throws out the effect of high-emitting reservoirs (i.e., cases like Brazil's Balbina Dam, even if they had been included), but these values cannot be omitted without biasing the result.

The IPCC (2006) guidelines appendix (IPCC, 2006, vol. 4, Appendix 3, p. Ap3.5) cites the following papers as the basis for their default value for CH_4 diffusion from reservoir surfaces in the wet tropics [i.e., Tier 1]: Abril et al. (2005), de lima (2002, 2005), Duchemin et al. (2000), Galy-Lacaux (1996), Galy-Lacaux et al. (1997), Keller and Stallard (1994), Rosa et al. (2006a), Therrien (2004). No default values are provided for bubbling [i.e., Tier 2], but the appendix states that "Useful information can be obtained from the following references": Abril et al. (2005), de lima (2002), Delmas et al. (2005), Duchemin (2000), Duchemin et al. (1995, 1999, 2006), Huttunen et al. (2002), Rosa et al. (1996, 2004), Soumis et al. (2004), Therrien (2005) (IPCC, 2006, vol. 4, Appendix 2, p. Ap2.2). No references or default values are given for degassing at the turbines [i.e., Tier 3], although the very good (and widely ignored, see Section 3.3) advice is given that "CH_4 concentrations upstream and downstream of dams would be needed for estimating degassing emissions" (IPCC, 2006, vol. 4, Appendix 3, p. Ap3.5). Note that none of the papers listed above were used in the IPCC special report (see Table 1).

The IPCC classifies reservoirs as "wetlands," but a revision of the wetlands section of the IPCC (2006) guidelines undertaken from 2011 to 2013 explicitly excluded revision of the portion on reservoir emissions (IPCC, 2014, p. O.4). The authors were instructed that: "Flooded lands (reservoirs) are specifically excluded as the TFI [Task Force on National Greenhouse Gas Inventories] does not consider the underlying science to be sufficiently developed" (IPCC, 2011, p. 3). This position means that, in practice, hydroelectric emissions will continue to be considered zero or near zero, despite substantial evidence that tropical dams emit significant amounts of greenhouse gases (e.g., Abril et al., 2005; Fearnside, 2002a, 2013; Fearnside and Pueyo, 2012; Kemenes et al., 2007). While estimates of amounts emitted are subject to uncertainty, as is the case for all forms of emission, the appropriate response is to use the best scientific data available at each point in time. If a conservative position is desired for policy making on climate change, this would mean using values at the *high* end of available estimates, not essentially assigning a value of zero to this source.

Because methane was relegated to an appendix in the IPCC (2006) guidelines, reporting continues to be voluntary even after these guidelines came into effect in 2015 (Mäkinen and Khan, 2010). The result is likely to be that tropical hydropower emissions remain virtually absent from the global accounts.

3. Reasons for underestimated emissions

3.1. *Turbines ignored*

When water is released from the turbines it is under considerable pressure—for example, in the case of Brazil's Tucuruí Dam the pressure is approximately four atmospheres from the weight of the water at the level of the turbine intakes (currently at 40 m depth), plus one atmosphere from the air above the reservoir. This pressure is suddenly reduced to one atmosphere as the water emerges from the turbines, causing an immediate emission of gases. Much of this emission will occur almost immediately. Many estimates of hydroelectric emissions simply ignore emissions from the turbines and spillways, including the estimates in Brazil's first national inventory of greenhouse gas emissions (Brazil, MCT, 2004). Brazil's second national inventory and the emissions report released as a prelude to the third national inventory have ignored emissions from hydroelectric dams altogether (Brazil, MCT, 2010; Brazil, MCTI, 2013). Most other countries have also ignored these emissions, since reporting them is currently optional.

3.2. *Trees ignored*

Another emission source often ignored is CO_2 from the above-water decay of wood in trees left standing in the reservoir (e.g., in the comparisons in the IPCC's Special Report on Renewable Energy). This can be substantial in Amazonian reservoirs (e.g., Abril et al., 2013; Fearnside, 1995, 2009). The emission from decaying trees occurs in the first few years of the reservoir's life, making this emission particularly important from the point of view of the interests of human society (see Section 3.7).

3.3. *Incomplete counting of downstream emissions*

What is meant by "downstream emissions" varies among authors, the term sometimes being used to refer both to the emission from degassing as the water emerges from the turbines and to the emission from the water surface in the river as it flows downstream of the dam, and sometimes being used only for the river surface flux. Flux measurements in the river well below the outlet from the dam will miss most of the emission, which is predominantly in the first meters below the turbines.

An influential study was undertaken by FURNAS (a company that generates 40% of Brazil's electricity, mostly in dams outside of Amazonia). The company released a finding that dams are 100 times better than fossil fuels from the point of view of greenhouse-gas emissions (Garcia, 2007). Omission of emissions from degassing at the turbines and spillways is a major reason why the study (Ometto et al., 2011, 2013) produced such low values for emissions. The measurements of downstream fluxes at the Serra da Mesa and Xingó Dams only began 500 m below the dams (da Silva et al., 2007), while at the Furnas, Estreito and Peixoto Dams measurements began 50 m downstream (dos Santos et al., 2009, p. 835). The FURNAS study also found relatively low emissions from the river surface in part because the dams studied are located in the *cerrado* (central-Brazilian savanna), where emissions can be expected to be lower than in Amazonia. Measurements by Guérin et al. (2006) in the rivers below three humid tropical dams (Petit Saut in French Guiana and Balbina and Samuel in Brazilian Amazonia) showed high methane emissions in the rivers downstream of the dams, even though degassing from the turbines was not included.

Getting flux measurements from nearer to the turbines is not enough for a reliable estimate of the turbines as an emissions source, no matter how close one gets. The only practical way to assess the emissions from the water passing through the turbines is to use concentration measurements from water samples taken at the appropriate depths above and below the dam, and calculate the emissions by difference. The emission at the outlet is sufficiently fast that there would only be a minimal effect from bacteria in the water converting part of the CH_4 to CO_2 before it reaches the atmosphere. When calculations are based on differences in concentration, the amounts of methane emitted are large, leading to the conclusion that more emissions than fossil fuel were produced for a substantial period after the reservoirs were formed at number of Amazonian dams, such as Tucuruí (Fearnside, 2002a), Curuá-Una (Fearnside, 2005a), Samuel (Fearnside, 2005b) and Balbina (Kemenes et al., 2007, 2008), as well as calculating such emissions at planned projects such as The Altamira Complex composed of the Belo Monte and Babaquara/Altamira Dams (Fearnside, 2009).

Another way that the counting of downstream emissions can be incomplete is to cut off consideration of fluxes beyond a given distance downstream, for example 1 km in the FURNAS study (e.g., Ometto et al., 2011). Unfortunately, emissions continue beyond this cutoff distance; they have been measured at the Balbina, Samuel and Petit Saut Dams (Gosse et al., 2005; Guérin et al., 2006; Kemenes et al., 2007).

3.4. *Underestimated methane concentrations*

Estimates of turbine emissions (including my own) that use data on CH_4 concentration in water at the depth of the turbines based on measurements in samples collected using traditional Ruttner bottles have underestimated these concentrations and the consequent emissions when the water is released below the dam. The underestimate is roughly by a factor of two. This is because part of the methane that is dissolved in the water comes out of solution when the Ruttner bottle is raised to the surface, and the water drawn from the sampler with a syringe for chemical analysis has a lower CH_4 concentration than the water at the bottom of the reservoir. A sampler designed to capture and measure this methane resulted in concentration values 116% higher than values for samples obtained simultaneously with Ruttner bottles from water at 30-m depth in Brazil's Balbina reservoir (Kemenes et al., 2011).

3.5. *Extrapolation from non-tropical reservoirs*

Reservoirs in the humid tropics emit much more methane than do reservoirs in other climatic zones (Barros et al., 2011; Demarty and Bastien, 2011). Many claims of low emissions from tropical hydroelectric dams are based on studies outside of the humid tropics. In Brazil, important examples include the Environmental Impact Study (EIA) for the Belo Monte Dam, which is under construction in a tropical rainforest area on the Xingu River in the state of Pará (Brazil, Eletrobrás, 2009, vol. 5, p. 47; see Fearnside, 2011). In this case, the estimate for the reservoir's future emission was a mean of flux measurements from two reservoirs, Tucuruí and Xingó. In the case of Xingó, the dam is in the semi-arid northeast of Brazil and would clearly have much lower emissions than an Amazonian dam like Belo Monte.

3.6. *Outdated global warming potential (GWP) for methane*

In accounting for emissions under the UNFCCC, non-CO_2 greenhouse gases are converted to CO_2-equivalents (CO_2e) by multiplying the number of tons emitted of each gas by a global-warming potential (GWP). Each gas has a characteristic radiative forcing, which represents its effectiveness in blocking the passage of infra-red radiation through the atmosphere on a near-instantaneous basis: radiative forcing is the net change in energy flow at the tropopause (the division between the troposphere and stratosphere at about 10-km altitude) caused by a given amount of gas after a delay of "few months" for stratospheric temperatures to equilibrate (Shine et al., 1995, p. 170). Including indirect effects, methane has a much higher radiative forcing than CO_2 on a mass basis: 595 times more per ton of each gas present in today's atmosphere (Hartmann et al., 2013, Supplementary Material, Appendix 2, p. 2SM-4; Myhre et al., 2013, Supplementary Material, Appendix 8, p. 8SM-13). Each gas also has a characteristic average atmospheric lifetime (the number of years a ton of the gas remains in the atmosphere, causing global warming). A ton of methane has a high impact while it remains in the atmosphere but has an average lifetime of only 12.4 years (Myhre et al., 2013, p. 714). A ton of CO_2 has a much weaker effect in each year that it is present, but the average lifetime is long—approximately 40% of an emission remains in the atmosphere after one century (Myhre et al., 2013, Supplementary Material, Appendix 8, p. 8SM-16). The GWP represents an integration over a time horizon, such as 20 years or 100 years, of the radiative forcing of one ton of the gas emitted at the beginning of the period, as compared to one ton of CO_2 emitted simultaneously. The IPCC's use of GWPs is explained by Albritton et al. (1995, pp. 215-219). As the time horizon for the GWP lengthens, the importance of methane declines relative to CO_2.

The GWP that has been most frequently used to convert the impact of methane emissions to CO_2-equivalents is 21, meaning that one ton of CH_4 gas has the same impact on global warming as 21 tons of CO_2 over a 100-year time horizon with no discounting for time. This is the GWP value from the IPCC's 1995 Second Assessment Report (Schimel et al., 1996) that was adopted by the Kyoto Protocol for use until the end of 2012 and was used in all national inventory accounting through the same year. However, the estimates for the GWP of methane have since been successively revised upward: to 23 in the IPCC's 2001 Third Assessment Report (Ramaswamy et al., 2001) and to 25 in the 2007 Fourth Assessment Report (Forster et al., 2007). The 2013 Fifth Assessment Report revises this to 28 if the same assumptions are maintained (i.e., ignoring all feedbacks), but presents a value of 34 for methane that includes indirect effects not considered in the previous IPCC reports (Myhre et al., 2013, p. 714). If a time horizon of 20 years is used instead of 100 years, this value increases 86 (Myhre et al., 2013, p. 714). A rapid and sustained reduction in methane emission is a necessary part of any strategy to maintain average temperature below the 2 °C limit for increase above the pre-industrial mean, as agreed in Copenhagen in 2009 under Decision 2/CP.15 (Shindell et al., 2012). Since methane is the main emission from hydropower and this gas is almost absent from fossil fuel emissions, these revisions make a substantial difference in the impact attributed to hydropower as compared to fossil fuels. If a GWP value of 34 is used instead of the value of 25 that will be used until 2017, the impact is 36% higher. If a value of 86 is used the impact of methane from dams is 244% higher.

Decisions on what GWP values to use in accounting under the UNFCCC are made by representatives of national governments at the annual Conferences of the Parties (COPs). At the UNFCCC 16th Conference of the Parties in Cancun (COP-16) in 2010 Brazil had a prominent role in arguing for maintaining the use of a lower GWP value for methane than that indicated by the IPCC's most recent report at the time (see: CAN, 2010). Brazil relies on hydropower for almost 80% of its electricity and has massive plans for dam construction in its Amazon region (e.g., Brazil, MME, 2013).

The use of older GWPs despite more recent IPCC estimates extends to all accounting under the UNFCCC, not just dams. In 2011 at COP-17 the decision was made to use GWPs from the IPCC's 2007 Fourth Assessment Report beginning in 2015 (Decision 15/CP.17, Paragraph 2).

3.7. *Ignoring the value of time*

This is perhaps the most fundamental factor leading to understatement of the importance of hydroelectric emissions to global warming. A wide range of opinions exist on the question of how much value, if any, should be given to time in assessing the value of greenhouse gases that are emitted or prevented from being emitted. Whether a ton of carbon emitted today has the same value as a ton emitted a century or more in the future is critical in deciding what to do about global warming, especially for decisions on dams.

Value is attributed to time in two ways. One is by defining a time horizon after which no consideration is given (for example the 100-year time horizon for GWPs used under the Kyoto Protocol). This means that by delaying an emission, part of the impact is pushed beyond the end of the time horizon and written off. The longer the time horizon, the less the value given to time. The other way is by giving a decreasing weight to costs and benefits (in this case emissions and avoided emissions) at each year in the future (Fearnside et al., 2000). The most common means of weighting is by applying a discount rate to each year, where the weight attributed decreases by a fixed percentage with each successive future year. Both a time horizon and a non-zero discount rate can be used together. Various other alternatives exist both for time horizons and time-preference weighting (Fearnside, 2002b,c). The value attributed to time is an ethical and political decision, not a scientific one. Nevertheless, an assumed value for time is present in all comparisons of emissions, whether or not this assumption is admitted to explicitly.

Opinions on the appropriate discount rate for emissions range from zero over a 100-year period (Kirschbaum, 2006; see Dornburg and Marland, 2008; Fearnside, 2008b) and even for an infinite period (as implied by Greenpeace calls for permanence of carbon sequestration on "geological" time scales), to a value equal to that used for financial decisions, that is, around 10%/year in real terms (e.g., van Kooten et al., 1997). This author argues for a small but non-zero value for time, equivalent to a discount rate on the order of 1–2% per year (Fearnside, 2002b). It is important to note that a non-zero value for time for global warming is not dependent either on a selfish perspective for the current generation or on translating all impacts into monetary terms: global warming is expected to result in many human deaths, which is an entirely separate form of impact from monetary losses, and delaying warming by a given number of years saves lives over the period of the delay (Fearnside, 1998).

The time horizon used is at least as important as the choice of a discount rate, both in deriving GWP values and in accounting for emissions. The IPCC's Fifth Assessment Report makes clear that "There is no scientific argument for selecting 100 years compared with other choices (Fuglestvedt et al., 2003; Shine, 2009). The choice of time horizon is a value judgment because it depends on the relative weight assigned to effects at different times." (Myhre et al., 2013, pp. 711–712).

The longer the time horizon used, the greater the distortion if a zero discount rate is applied (as in the case of the current GWP values derived by the IPCC). One way that accounting studies often justify long time horizons without discounting is to base computations on a full life cycle, with the common assumption that a dam will last 100 years. Note that these are often not true lifecycle analyses due to omission of the decommissioning (removal) of the dam at the end of the cycle. For comparison of different generation options, such as fossil fuels and dams, it is essential that the same time horizon be used if a non-zero value of time is to be included (as through a discount rate). Comparison of a dam with an assumed 100-year useful life with a thermoelectric plant with an assumed 50-year life will produce a distorted result.

A hydroelectric dam emits large amounts of greenhouse gases in the first few years after it is built, which creates a global warming "debt" that is slowly paid off as electricity generated by the dam displaces fossil fuels in the succeeding years; in contrast to this, electricity generation from fossil fuels emits gases at a constant rate, with the emission occurring at the same time as the electricity is generated. This difference is critical in comparing dams to fossil fuels, with any value attributed to time weighing heavily against dams (Fearnside, 1996, 1997). The full emissions profile of a dam is a complex set of emissions credits and debits to CO_2, CH_4, and other gases over time. In contrast, fossil-fuel-fired power plants release emissions primarily when fuel is burned to generate electricity. The fact that dams emit methane with an intense but short-lived impact, while fossil fuels emit primarily CO_2 with a mild but long-lived impact, is also critical. Note, however, that in a number of countries, including Brazil, most new thermoelectric plants burn natural gas rather than coal or oil, and that gas pipelines supplying the plants leak methane.

The hydroelectric industry would like no form of time preference weighting to be applied to emissions in this century: the International Hydropower Association (IHA) advocates for basing all calculation on a 100-year time horizon with no discounting (e.g., Goldenfum, 2012). Unfortunately, we do not have 100 years to take effective measures to mitigate global warming, and it is the emissions within the next few years that will determine whether "dangerous" climate change can be avoided. Brazil's dam-building plans in Amazonia, for example, would release large amounts of greenhouse gases precisely in the time window when global warming must be controlled.

3.8. *Other factors underestimating emissions*

Various other factors often lead to underestimating emissions from tropical dams. One is "cherry picking" (selecting only cases that confirm one's conclusion). A second is assuming that dams are built on natural wetlands (which emit significant amounts of methane) instead of in the places with rapids and waterfalls that result in more power generation. A third is to assume that reservoir sedimentation will cancel emissions. A fourth is to assume that emissions will dwindle to zero, when in fact they can be maintained indefinitely (albeit at a lower level than during the initial emissions peak that follows flooding the reservoir). These factors are reviewed in the Supplementary Online Material.

4. The sociology of science and dam emissions

Both scientific research and its interpretation for policy are done by human beings who act within the context of their social and institutional environments. The journal *Climatic Change* hosted a debate over this issue between this author (Fearnside, 2004, 2006) and the then-head of Eletrobrás (Rosa et al., 2004, 2006b). The debate was refereed by Cullenward and Victor (2006), who pointed out that "A large proportion of the published work in this field comes directly from researchers connected to hydroelectricity companies, such as Eletrobrás or Hydro-Québec" and suggested as a result that "a mechanism is needed to remove any taint of interest so that CDM [Clean Development Mechanism] projects and national inventories can earn confidence. The international community has a mechanism readily at hand to fix the problem: a special report of the Intergovernmental Panel on Climate Change (IPCC)." A special report specifically on hydropower emissions has not been undertaken, but the IPCC's Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) included hydropower (Kumar et al., 2012). The lists of authors of the hydropower sections include staff from both Eletrobrás and Hydro-Québec (Kumar et al., 2012; Moomaw et al., 2012). In the IPCC, 2006 guidelines both of the two appendices dealing with reservoirs (Appendices 2 and 3) have authors from both Hydro-Québec and Eletrobrás (IPCC, 2006, volume 4, chapter 7, p. 7.2). McCully (2006) has documented the longstanding predominance of the hydropower industry in research concerning emissions from dams.

The IPCC special report has been criticized by the non-governmental organization (NGO) International Rivers for not discussing high methane emissions from tropical reservoirs, which is simply listed in a table, in contrast to much greater attention given to the low emissions in boreal and temperate regions (Parekh, 2011). The critique also points out that, contrary to normal IPCC practice, fully one-fourth of the section on emissions from hydropower is devoted to presenting preliminary results from an unreviewed scoping paper led by the International Hydropower Association (IHA), an industry group (IHA, 2008). The special report also highlights the IHA's more recent work on procedures for quantifying emissions (summarized in: IHA, 2010).

A proper accounting of emissions from tropical hydroelectric dams is essential to containing climate change. International negotiations under the UNFCCC are aimed at establishing quotas (assigned amounts) for national emissions such that the net global emission from all sources (including "natural" sources) is consistent with preventing atmospheric concentrations of greenhouse gases from reaching levels that cause "dangerous interference with the climate system" (UNFCCC, 1992, Article 2), now defined as 2 °C average temperature increase over pre-industrial levels. If national inventories submitted by each country do not reflect the true amount of emission because tropical hydroelectric dam emissions have been omitted or understated, then the assigned amounts negotiated under the UNFCCC will be insufficient to contain climate change and the impacts of passing the 2 °C threshold will ensue (e.g., Meinshausen et al., 2009).

5. Conclusions

The Intergovernmental Panel on Climate Change (IPCC) guidelines for national inventories of greenhouse-gas emissions need to be revised such that the required level of reporting on dams reflects the full extent of their emissions of all greenhouse gases. The IPCC also needs to conduct a thorough review of the subject independent of the hydropower industry.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2015.03.002.

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Supplementary online material for:

Emissions from tropical hydropower and the IPCC

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Additional reasons why hydropower emissions are often understated

In addition to the eight reasons reviewed in the text leading to underestimation of tropical hydropower emissions the following four reasons are also often present.

1. "Cherry picking" dams

"Cherry picking," or selecting only the cases that confirm one's conclusion, is one way that estimates of hydroelectric emissions can be downplayed. In Brazil, the Balbina Dam, which has very high methane emissions, was not included in the tabulation of dams in the country's first national inventory (Brazil, MCT, 2004, p. 154; see also Rosa et al., 2004), although the study's authors had previously published surface emission data from the dam (Rosa et al., 1997). Balbina represented approximately 40% of the area flooded by reservoirs in Brazil's Amazon rainforest areas at the time of the inventory. Balbina has been excluded from a number of discussions on Amazonian dams on the grounds that it is atypical and represents a mistake that would never be committed again. Unfortunately, Balbina has many parallels with dams that are likely to be built in the coming decades, especially the Babaquara (renamed Altamira) Dam upstream of Belo Monte (Fearnside, 2006, 2012).

2. Assumption that dams are built in wetlands

The net effect of a dam is the dam's emission minus what would have been emitted by the ecosystem without the dam, including forest in the area flooded by the reservoir. The US National Hydropower Association reacted to this author's first publication of results indicating high emissions from Amazonian dams (Fearnside, 1995) by declaring "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." (McCully, 2001). The International Hydropower Association even claimed that dams are a "zero-sum issue, new wetlands replacing old wetlands" (Gagnon, 2002). However, dams are not built in flat wetlands that emit methane, since locations with rapids or waterfalls result in much more power generation. The soils under upland forests in Amazonia are considered to be methane sinks (e.g., Keller et al., 1991).

The assumption of unrealistically high pre-dam emissions was not restricted to the hydropower industry's initial denials of a global-warming impact from dams. In the environmental impact study (EIA) for Brazil's controversial Belo Monte Dam the estimate of pre-dam emission was largely based on measurements in waterlogged soils that had recently been exposed by falling river levels, such that calculations effectively assumed that the reservoir area as a whole would be emitting very substantial amounts of methane (see Fearnside, 2011).

3. Assumption that reservoir sedimentation cancels emissions

The International Hydropower Association has argued that dams could have a positive effect by capturing carbon in the sediments deposited in the reservoirs, thus preventing this carbon from being emitted to the atmosphere (e.g., Gagnon, 2002). Reservoir sediments do contain carbon (Sikar et al., 2009). However, the carbon in the sediments is a two-edged sword, as this is also the source of carbon for methanogenesis under the anoxic conditions at the bottom of a reservoir. Carbon balance should not be confused with global-warming impact. Dams release carbon in the form of methane, with a much greater impact per ton of carbon than the CO_2 that would be released if carbon deposited in the sediments were instead allowed to flow downstream and be oxidized in the river. It should also be remembered that part of this carbon would not be oxidized in the river, but instead would be deposited either in ocean sediments. In the case of Amazonia some of this carbon would be transferred to the sediment deposits that continue to have a net accumulation in the Amazon floodplain (*várzea*). More of the carbon deposited in sediments is later released as gases in a reservoir than in the ocean, a factor that increases net global greenhouse-gas emissions (Mendonça et al., 2011, p. 63). Also, although water in the Amazon River is known to release large quantities of CO_2 (Richey et al., 2002), indicating oxidation of carbon carried in the river, there are also high emissions of CO_2 from Amazonian reservoirs and from the turbines and spillways of Amazonian dams (e.g., Kemenes et al., 2011).

4. Assumption that emissions dwindle to zero

The idea that hydroelectric emissions inexorably decline to zero is misleading. A strong decline in greenhouse-gas emissions in the first few years of a reservoir's life is a well-known pattern, but this does not mean that emissions will always continue to decline until they are virtually zero. Emissions can stabilize at a level well above zero where there is a renewable source of carbon such as the annual flooding of herbaceous vegetation in the drawdown zone when the water level is raised in the rainy season. Different reservoirs can have quite different water-management regimes, differing in the amount of vertical variation in the water level and in the area of the drawdown zone that is exposed when the water level is lowered. In Brazil's first national inventory the Três Marias reservoir in a *cerrado* (savanna) area in the state of Minas Gerais was the clear "champion" of methane emissions, emitting even more than the Amazonian dams that were included in the study (Brazil, MCT, 2004; Rosa *et al*., 2004). At the time of the measurements, the Três Marias reservoir was 36 years old and was therefore well past the initial peak in methane emission. The 9-m vertical variation in water level at Três Marias is a likely explanation of how CH_4 emissions can be maintained over time. Note that the time-path of methane emissions, with an large initial peak followed by long-term plateau at a lower level, adds greatly to the impact of dams in terms of human interests.

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