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Greenhouse Gas Emissions from Hydroelectric Dams in Tropical Forests

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ABSTRACT

Hydroelectric dams are not necessarily sources of "clean energy" because they produce greenhouse emissions that can be substantial. Carbon dioxide (CO_2) is emitted by above-water decay of trees left in the reservoir, and initially by below-water decay. Some carbon dioxide emission that would occur in the undammed river is avoided by carbon storage through sedimentation in the reservoir. Although biomass growth in the reservoir and drawdown zone provides a carbon source for CO_2 emission when the biomass decays under aerobic conditions, this part of the emission does not represent a net contribution to global warming because the same amount of carbon was removed from the atmosphere by photosynthesis when the biomass was produced. CO_2 emissions also come from materials and energy used during dam construction. Pre-dam forest carbon balance, with loss of carbon uptake by tropical forests in areas that are flooded, is no longer thought to be a significant factor on average, but would add to the impact of planned dams on relatively fertile soil near the Andes.

Nitrous oxide (N_2O) is emitted by reservoirs at a rate over three times higher than under tropical forests. This adds to the net impact of hydropower in tropical forest areas such as Amazonia.

Methane (CH_4) emissions represent a net contribution to global warming because, unlike CO_2, this gas is not removed from the atmosphere when biomass is produced. Methane has a much larger impact of global warming per ton of gas than does carbon dioxide. Carbon sources for methane are of two types: non-renewable and renewable. The non-renewable sources of carbon, such as the soil and the initial biomass of the terrestrial vegetation that is flooded, make a large emission pulse in the first few years, but then decline to low levels. The renewable sources, however, can continue to convert atmospheric CO_2 to CH_4 throughout the life of the dam, thus making the dam function as a "methane factory." Renewable carbon sources include the terrestrial weeds and grasses that grow in the drawdown zone when it is exposed each year, water weeds (macrophytes) that grow and die in the reservoir, algae and fungi, water pollution such as sewage entering the reservoir, and leaves and other organic matter washed into the reservoir from primary production in upstream watersheds. Calculation of net methane emissions

requires correction for the loss of pre-reservoir methane fluxes, including forest soils, termites and any wetlands that may have been flooded.

Not all methane produced is emitted, as some is oxidized to CO_2 before it can be released to the atmosphere. Methane release pathways are of two types: reservoir surface emissions (diffusion and bubbling) and outlet and downstream emissions (emissions at spillways, turbines and in the river downstream of the dam). Proposals exist to capture and use some of this methane, but none have been implemented so far.

Comparisons with fossil fuels require quantifying not only the magnitude but also the timing of emissions, including both direct and indirect emissions. The importance of time is essential, since dams and fossil fuels differ greatly in the time path of the emission. Hydroelectric dams produce emissions before any electricity is generated and have a very large peak of emission in the first few years, whereas thermoelectric plants produce almost all of their emissions spread over time in direct proportion to the electricity that is produced. Non-greenhouse impacts of dams also differ from those of fossil fuels and other alternatives both in magnitude and in their nature and timing.

INTRODUCTION

Although hydroelectric dams are often presented as “green” energy, meaning an energy source without greenhouse gas emissions, dams do, in fact, emit substantial amounts of gases (e.g., Fearnside, 2007, 2009a,b; Gunkel, 2009). The amounts emitted vary greatly depending on the geographical location, the age of the reservoir, external inputs of carbon and nutrients, and characteristics of the reservoir such as water flow, turnover time, area, depth, water level fluctuations and the positioning of the turbines and spillways. Dams in tropical areas emit more methane than do those in temperate or boreal areas (Barros *et al.*, 2011; Matthews *et al.*, 2005). Bastviken *et al.* (2011) estimated that reservoirs cover 500,000 km^2 worldwide and emit 20 million tons of methane (CH_4) annually. This is equivalent to 185 million tons of CO_2-equivalent carbon if calculated using the IPCC Fifth Assessment Report global warming potential (GWP) for methane of 34 for 100 years, or 1.7 billion tons if the 20-year GWP of 86 is used (Myhre *et al.*, 2013, p. 714). However, these numbers only include emissions from the surfaces of the reservoirs through ebullition (bubbling) and diffusion (emanation) – not the emissions that occur as methane-rich water emerges (under pressure) from deep in the water column through the turbines and spillways, which can more than double the total (e.g., Abril *et al.*, 2005; Fearnside, 2009a,b; Kemenes *et al.*, 2008). However, the amount of information needed for reliable estimates of these emissions on a dam-by-dam basis makes a global estimate difficult at present.

The factors mentioned above – omission of major emissions sources such as turbines, much higher methane emission from tropical dams as compared to other regions, and ignoring or downplaying the importance of time – explain the conclusion of the Intergovernmental Panel on Climate Change (IPCC) *Special Report on Renewable Energy Sources and Climate Change Mitigation* that hydropower has 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). In the IPCC review none of the 11 sources used from all climatic zones appears to concern tropical dams (Moomaw *et al*., 2012, p. 986). However, it is in tropical areas such as Amazonia that much of the World's hydroelectric development is expected in the coming decades.

The review that follows focuses on dams in tropical forest areas in South America (Figure 1). Much of the information is applicable to other tropical areas and, to a certain extent, to subtropical and other areas. The rapid expansion of dams planned in Amazonia makes advances in the measurement and modeling of hydroelectric emissions an urgent priority. Brazil's 2013-2022 Decennial Plan for Energy Expansion calls for 18 new large dams in the country's Legal Amazon Region (Brazil, MME, 2013).

[Figure 1 here]

TYPES OF EMISSION

Carbon Dioxide (CO_2)

Hydroelectric dams emit greenhouse gases in various ways throughout the lives of these projects. First, there are emissions from the construction of the dam from the cement, steel and fuel that are used. These emissions are greater than those for an equivalent facility for generating the same amount of electricity from fossil fuels or from alternative sources such as wind and solar. The emissions from dam construction also occur several years before generation of electricity begins – longer than the lead time for other sources. Because time has value for global-warming impacts, this time difference adds to the impact of hydropower relative to most other sources (Fearnside, 1997). The construction emissions are estimated at 0.98 million tons of CO_2-equivalent carbon for Brazil's planned Belo Monte Dam and 0.78 million tons for the Babaquara/Altamira Dam if calculated without weighting for time (Fearnside, 2009a,b).

When a landscape is flooded by a reservoir, the emissions and uptakes of the pre-dam landscape must be deducted from the corresponding gas fluxes from the reservoir in order to assess the net impact of the dam. In tropical forest areas the carbon balance of the forest is a critical factor. In the 1990s many believed the Amazon forest to be a major sink for atmospheric carbon, thereby increasing the net impact on global warming of converting forest to other uses, including reservoirs. However, correction for a series of problems in the measurement techniques has subsequently reduced the estimates of forest uptake by more than five fold, and forest is no longer thought to be a major carbon sink on average (e.g., Araújo *et al.*, 2002; Fearnside, 2000; Kruijt *et al*., 2004).

The amount of carbon uptake by Amazonian forest varies substantially with location (Ometto *et al*., 2005). The greatest uptake rates were estimated from tree-growth measurements in Peru and Ecuador (Phillips *et al*., 1998, 2004); unfortunately, there are no towers at these sites for comparable eddy correlation measurements. Uptake rates decline from the Andes to the Atlantic Ocean, a pattern that has been attributed to a corresponding gradient in soil fertility (Malhi *et al.*, 2006). In 2010 Brazil signed an agreement with Peru to allow the Brazilian government electricity company (ELETROBRÁS) to build the first six of over a dozen planned dams in the Amazonian portion of Peru. One of these highly controversial dams (Inambari) is currently suspended by presidential decree.

Deforestation emissions can be substantial as a result of population displacement and stimulation of clearing in the areas surrounding new dams and their access roads, as occurred at Brazil's Tucuruí Dam (Fearnside, 2001). Displaced emissions can occur not only from lost land use, but also from lost water use, for example to replace fish that were formerly produced in the undammed river. This is a concern for dams under construction on the Madeira River in Brazil (Fearnside, 2014a).

Another major source of emission is the carbon released from above-water decay of the trees that are killed by flooding (Abril *et al*., 2013). The trees are generally left standing in the reservoir, where they project above the water and rot in the presence of oxygen, releasing their carbon as CO_2. Additional trees are killed in unflooded forest near the shoreline, including forest on islands in the reservoir, due to the rise in the water table. This addition is greatest in reservoirs with convoluted shorelines and many islands, such as Brazil's Balbina Dam (Feitosa *et al.*, 2007). The release of carbon from tree death begins when the reservoir is first filled (well before any generation of electricity), and the bulk of the emission occurs within the first few years of reservoir life. The value of time therefore makes this up-front impact a substantial count against hydropower as compared to generation from fossil fuels, which release the great majority of their CO_2 at the same time that the electricity is produced (e.g., Fearnside 1997). For 1990 (the standard year for the initial greenhouse inventories under the Climate Convention), the annual emission from above-water decay of flooded trees (not counting shoreline mortality) was estimated at 6.4 million tons of carbon for Balbina (Fearnside, 1995), 1.1 million tons for Samuel (Fearnside, 2005a) and 2.5 million tons for Tucuruí (Fearnside, 2002). The Babaquara/Altamira dam, 'unofficially' planned for construction upstream of Belo Monte, would, in conjunction with Belo Monte, be likely to become the all-time "champion" for these emissions, with an average in the first ten years estimated at 9.6 million tons of carbon emission annually from above-water decay of flooded trees plus 0.07 million tons from shoreline emissions (Fearnside, 2009a,b).

The water in the reservoir also emits carbon dioxide, either through bubbling or diffusion through the reservoir surface or from the water being released through the turbines and spillways. This CO_2 comes from various sources, and it is important to avoid double-counting of the carbon. Some is from underwater decay of the trees initially present in the reservoir, either as CO_2 being produced directly if the tree biomass decays in the surface layer of water that contains oxygen, or indirectly if the biomass decays in the deep layers where there is little or no oxygen and the carbon is released as methane, some of which is subsequently converted to CO_2 by bacteria in the surface layers. This pathway, from tree biomass to dissolved methane to dissolved CO_2, is believed to be the major source of CO_2 released from water at Balbina (Kemenes *et al.*, 2011).

Carbon dioxide is also released from soil carbon in the flooded land. Like the trees, this is a fixed source that will eventually be depleted. Similarly, the emission is greatest in the first years. Researchers at the Petit Saut Dam in French Guiana believe soil carbon to be the major source for both CO_2 and methane produced in the initial pulse of emission after flooding (Tremblay *et al.*, nd [C. 2005]).

CO_2 emission from the water includes the carbon released from renewable sources, in addition to those from fixed sources such as trees and soil carbon. Carbon also enters the reservoir as dissolved organic carbon (from leaching) and as sediments coming soil erosion throughout the hydrographic basin upstream of the reservoir. This carbon is continually being removed from the atmosphere by photosynthesis in the standing forest and converted to soil organic carbon and to direct exports of biomass carbon through the deposition of litter on the forest floor. Substantial amounts of the still-undecomposed litter are washed into the streams during torrential rains (Monteiro, 2005). Some of this carbon is stored in the sediments at the bottom of the reservoir. This storage in sediments has been claimed to be a carbon benefit of dams (e.g., Gagnon, 2002). However, a full accounting would require deducting the portion of the carbon that otherwise would have been carried down the river and deposited in ocean sediments. Some would have been released from the water in the downstream river, the water in the Amazon River being known as a significant emitter of CO_2 (Richey *et al.*, 2002).

Other renewable sources of carbon include photosynthesis in the reservoir itself from phytoplankton, algae and water weeds (macrophytes). There is also a renewable source from the herbaceous plants that grow in the drawdown zone. This zone is the mudflat that is exposed around the edge of the reservoir each time the water level is lowered for power generation in the dry season. Soft herbaceous plants, such as weeds and grasses, grow quickly in this zone as soon as the water level goes down. The drawdown area can be vast: 659.6 km^2 at Balbina (Feitosa *et al.*, 2007) and 3580 km^2 at the 'unofficially' planned Babaquara/Altamira reservoir (Fearnside, 2009a,b). When the water rises again, the plants are killed and then decay quickly because they are soft (in contrast to wood, which contains lignin and decays very slowly underwater). When oxygen is present in the water this carbon will be released as CO_2, but because the weeds are rooted to the bottom, much of the decay will be in the oxygenless water at the bottom of the reservoir and will produce methane. As with methane from other sources, part of this dissolved gas will be oxidized to CO_2 by bacteria before it reaches the surface. The remainder will be released as methane, making the drawdown zone a "methane factory" that will continually convert atmospheric CO_2 into methane, which is a much more potent per ton of gas in provoking global warming (Fearnside, 2008a,b).

The CO_2 in the water that has come from renewable sources such as forest litter, phytoplankton, algae, water weeds, and the drawdown zone vegetation, must be distinguished from CO_2 coming from initial fixed sources such as flooded trees and soil carbon. The portion from fixed sources represents a net contribution to global warming, taking care not to double-count any of the carbon. The portion coming from renewable sources, however, does not represent a contribution to global warming because the same amount of CO_2 that has been removed from the atmosphere by photosynthesis is simply being returned to the atmosphere in the same form (CO_2) after a period of months or years. If all of the dead tree biomass is counted as an emission from "deforestation," or by difference in biomass stocks between forest and "wetland," as in the case of the IPCC methodology (Duchemin *et al.*, 2006; IPCC, 1997) used in Brazil's first and second inventories under the Climate Convention (Brazil, MCT, 2004, 2010), then some of the same carbon is being counted twice. Calculations of reservoir impact that count all of this CO_2 as a global warming impact (e.g., Saint Louis *et al.*, 2002; dos Santos *et al.*, 2008; Kemenes *et al.*, 2011) therefore err on the high side for this portion of the emission. Research to better quantify the carbon sources from which the reservoir's CO_2 emission is derived should be a high priority. In the meantime, this author has opted to count only methane emissions from the reservoir surface and from the water passing through the turbines and spillways – not CO_2 from these sources (e.g., Fearnside, 2002, 2005b, 2009a,b). Carbon dioxide is only counted for above-water decay of dead trees.

Nitrous Oxide (N_2O)

Nitrous oxide (N_2O) is another greenhouse gas with a contribution from reservoirs. Amazonian reservoir surfaces emit an average of 7.6 kg N_2O km^{-2} day^{-1} (Lima *et al.*, 2002), or 27.6 kg ha^{-1} $year^{-1}$. Unflooded forest soil emits 8.7 kg ha^{-1} $year^{-1}$ (Verchot *et al.*, 1999, p. 37). The reservoirs therefore emit more than three times as much as the forests they replace. Considering the most recent global warming potential for nitrous oxide from the Intergovernmental Panel on Climate Change (IPCC), each ton of N_2O has an impact equivalent to 298 or 264 tons of CO_2 gas over a 100-year or 20-year period, respectively (Myhre *et al.*, 2013, p. 714). Amazonian reservoirs therefore emit 2.26 or 2.00 Mg ha^{-1} $year^{-1}$ of CO_2-equivalent carbon, versus 0.71 or 0.63 for the forest, leaving a net emission of 1.55 or 1.37 Mg ha^{-1} $year^{-1}$ of CO_2-equivalent carbon. For a 3000-km^2 reservoir like Brazil's Balbina Dam this represents 465,000 or 412,000 tons of carbon equivalent per year. Measurements of N_2O emissions at the Petit Saut reservoir in French Guiana, and the Fortuna reservoir in Panamá indicate emissions around twice those of tropical forest soils (Guérin *et al.*, 2008). Emissions from forest soils vary considerably among locations, indicating the importance of site-specific measurements for estimating pre-dam emissions. Unlike CO_2 and CH_4, almost all of the N_2O emission from dams occurs through the reservoir surface rather from downstream degassing (Guérin *et al.*, 2008). The range of emission is large: considering only emissions from the reservoir surface, the share of the global warming impact from N_2O ranges from 29 to 31% of the surface emission total considering CO_2, CH_4 and N_2O in four reservoirs in tropical forest areas: Tucuruí, Samuel, Petit Saut and Fortuna (Guérin *et al.*, 2008). In reservoirs that are not in tropical forest areas the emissions of N_2O are much lower.

Methane (CH_4)

Methane emission is a major contribution of hydroelectric dams to global warming. Methane (CH_4) is formed when organic matter decays without oxygen being present, for example at the bottom of a reservoir. The water in a reservoir stratifies into two layers: a surface layer (the epilimnion) where the water is warmer and is in contact with the air, and a bottom layer (the hypolimnion) that lies below a separation known as the "thermocline," because the water below this point is much colder. If expressed in terms of dissolved oxygen content, the separation, which occurs at approximately the same depth of 2-10 m, is known as the "oxycline." The water below the thermocline or oxycline does not mix with the surface water, except for occasional events where the stratification breaks down and bottom water rises to the surface, killing many fish. In Amazonia this occurs during cold snaps (*friagens*), which are a climatic feature in the western but not in the eastern part of Amazonia. Balbina lies approximately at the eastern limit of this phenomenon and has experienced several fish dieoffs from overturning water during cold snaps. Under normal conditions, with the cold water at the bottom staying separated below the thermocline, the dissolved oxygen in the bottom water is quickly depleted in oxidizing some of the leaves and other organic matter on the bottom of the reservoir, and thereafter essentially all decay must end in CH_4 rather than CO_2. Higher concentrations of gases can be dissolved in water at the bottom of the reservoir because the water is cold and under high pressure.

Natural lakes and wetlands, including the *várzea* and the *pantanal*, are significant global sources of methane (Devol *et al.*, 1990; Hamilton *et al.*, 1995; Melack *et al.*, 2004; Wassmann & Martius, 1997). A hydroelectric reservoir, however, is a substantially greater source of CH_4 per area of water because of one crucial difference: the water leaving the reservoir is drawn from the bottom instead of the surface. Both natural lakes and reservoirs will emit CH_4 through bubbles and diffusion at the surface, but in the case of the reservoir there is an additional source of CH_4 from water passing through the turbines and spillways. These take water from below the thermocline, where it is saturated with methane. The reservoir is like a bathtub, where one pulls the plug and the water drains out of the bottom rather than overflowing from the top like a lake. Because the water emerging from the turbines is under high pressure, the sudden drop in pressure as it emerges downstream will cause most of the methane to form bubbles and be released to the atmosphere. Over a longer time, the warming of the water as it flows downstream below the dam will result in further reduction in solubility and increase in release of gas (Le Chatalier's principle).

For gas in the water flowing downstream below a dam, release to the atmosphere is sufficiently fast for most of the CH_4 to escape being converted to CO_2 by bacteria in the water. In fact, the major release is immediately below the turbines and even inside the turbines themselves. This is the reason why gas flux measurements from the water surface in the river below a dam are not sufficient to measure the impact of emissions from water passing through the turbines—much of the emission is escaping measurement. This is the main explanation, for example, for why the research group mounted by FURNAS (a power company that supplies 40% of Brazil's electricity) was able to claim that hydroelectric dams were "100 times" better than fossil fuels in terms of global warming (Garcia, 2007). Such low values for emissions are in part because the dams studied were in the *cerrado* (central Brazilian savanna) rather than tropical forest, and because the estimates omit emissions from degassing at the turbines and spillways (Ometto et al., 2011, 2013). In fact, the flux measurements began at distances below the dam ranging from 50 m at the Furnas, Estreito and Peixoto dams (dos Santos *et al.*, 2009, p. 835) to 500 m at the Serra da Mesa and Xingó dams (da Silva *et al.*, 2007). They also ignored emissions more than 1 km below the dams (Ometto *et al.*, 2011). The only way to estimate the release without such major biases is to base it on the difference in concentration of CH_4 in the water above and below the dam (e.g., Fearnside, 2002; Kemenes *et al.*, 2007).

Estimates of the impact of Amazonian dams on global warming have varied by many fold. Most people hearing about the different estimates through the press have no information about how the underlying measurements were made and what is included or omitted from the estimates. Examining the original studies on all sides of the debate is essential. Both sides of the extensive debate over greenhouse gas emissions are available in the “Amazon Controversies” section of the website http://philip.inpa.gov.br.

A brief review of reasons for the very disparate results is in order. First, omission of the emissions from the water passing through the turbines and spillways is one that should be obvious. This omission has been a longstanding feature of official Brazilian estimates, as was highlighted during the memorable debate on this topic in the journal *Climatic Change* (see: Rosa *et al.*, 2004, 2006; Fearnside, 2004, 2006a). The same omission applies to the greenhouse gas emissions estimate for dams in Brazil’s first national communication under the Climate Convention (Brazil, MCT, 2004; Rosa *et al.*, 2002), with results more than ten times lower than those of this author for dams such as Tucuruí and Samuel (Fearnside, 2002, 2005a). Omission of the turbines and spillways was the major explanation. The major role played by emissions from water released by the turbines is clear from direct measurements above and below the dams at Petit Saut in French Guiana (Abril *et al.*, 2005; Delmas *et al.*, 2004; Galy-Lacaux *et al.*, 1997, 1999; Guérin, 2006) and at Balbina in Brazil (Kemenes *et al.*, 2007, 2008, 2011).

In Brazil’s first inventory of greenhouse gases, hydropower emissions were calculated for nine dams, but the results were confined to a box on the side and not included in the tally of the country’s emissions (Brazil, MCT, 2004, pp. 152-153). In the second national inventory (Brazil, MCT, 2010), hydroelectric emissions were omitted altogether. However, although the impact of CO_2 release from the trees killed by the reservoir is a major omission of many discussions of the role of dams in global warming, in the case of Brazil’s second national inventory the CO_2 release from biomass loss in converting forest to “wetlands” is included as a form of land-use change.

Exaggeration of the pre-dam emission is another way that the net emissions of dams can be underestimated. As already mentioned, natural wetlands are significant sources of methane, and this has been used to argue that the landscape flooded by a dam would have been emitting large amounts of methane anyhow if the dam had not been built. For example, the International Hydropower Association (IHA) considered hydroelectric emissions to be a “zero-sum” issue because they would not exceed pre-dam emissions (Gagnon, 2002). In the Environmental Impact Study (EIA) for the Belo Monte Dam, the area to be flooded was assumed to be emitting 48 mg CH_4 m^{-2} day^{-1} prior to creation of the reservoir, based on two sets of measurements of emission from the river surface and soil at sites near the edge of the river (Brazil, ELETROBRÁS, 2009, Appendix 7.1.3-1; see Fearnside, 2011). Most of the soil emission measurements in the wet season were in waterlogged areas that had recently been exposed by the falling water level (Brazil, ELETROBRÁS, 2009, Appendix 7.1.3-1, p. 72), resulting in their high CH_4 emission heavily influencing the mean used for all of the land area to be inundated by Belo Monte. However, hydroelectric dams are normally built in places with well-drained soils, sites with rapids and waterfalls being chosen rather than flat wetlands. This is because the steep topography results in greater generation of power. The seasonally flooded soils along the river cannot be generalized to a reservoir area, which in Amazonia is usually unflooded upland (*terra firme*) forest. The soil under *terra firme* forest is generally considered to be a methane sink, rather than a source (Keller *et al.*, 1991; Potter *et al.*, 1996). An unrealistically high estimate of pre-dam emission leads to an underestimate of the net impact. In the case of the Belo Monte EIA, the 48 mg CH_4 m^{-2} day^{-1} is subtracted from the EIA's estimate of 70.7 mg CH_4 m^{-2} day^{-1} for emission in the reservoir (an underestimate for various reasons, including using as half of the estimate a set of measurements at the Xingó Dam in Brazil's semiarid northeast region where emissions would be lower than at an Amazonian dam), leaving only 70.7 – 48.0 = 22.7 mg CH_4 m^{-2} day^{-1} as the net emission.

Another source of lower estimates of hydropower emissions in Brazil is a mathematically erroneous power-law correction that has been repeatedly applied in calculating bubbling and diffusion emissions from reservoir surfaces. This stems from a doctoral thesis (dos Santos, 2000), which is the basis of an ELETROBRÁS report (Brazil, ELETROBRÁS, 2000). The report calculates and tabulates the emissions for all 223 large dams in Brazil at that time, with a total water surface of 32,975 km^2 -- an area larger than Belgium. The correction continues to be applied (e.g., dos Santos *et al.*, 2008). These ELETROBRÁS adjustments reduce the emission estimates for surfaces by 76% as compared to the simple mean of their measured values in the data from the same study (see Pueyo & Fearnside, 2011a,b). The problem is that bubbles from the reservoir surface normally occur in sporadic episodes with intense bubbling for a short period, followed by long periods with few bubbles. Because the number of samples is inevitably insufficient to represent these relatively infrequent events, a power-law correction can be applied to the measurement data. However, the rare but high-impact events raise rather than lower the real mean emissions. In fact there are at least five major mathematical errors in the ELETROBRÁS calculation, including a reversal of the sign from positive to negative. Note, however, that the underestimate from the errors in application of the power-law correction not only apply to methane but also to CO_2 bubbling, not all of which is a net contribution to global warming. The correct application of the power law results in estimates of surface emissions of methane that are 345% higher than the ELETROBRÁS estimates (see: Pueyo & Fearnside, 2011a,b).

Inappropriate sampling methodology is another way that can lead to emissions several times lower than they should be (Fearnside & Pueyo, 2012). As already mentioned, attempting to estimate the turbine and spillway emissions by relying only on surface-flux measurements below a dam is fated to miss much of the emission, resulting in gross underestimates of the total impact. This is a major factor in low estimates by FURNAS and ELETROBRÁS. Even concentration-based estimates (including my own) have underestimated emissions because of the sampling methodology used to obtain water from near the bottom of the reservoir. The almost universal method is the Ruttner bottle, which is a tube with "doors" that open at each end. The tube is lowered on a cord with both doors open, then the doors close and the bottle is pulled up to the surface. Water is then removed for chemical analysis. The problem is that gases dissolved in the water under pressure will form bubbles inside the Ruttner bottle as it is pulled to the surface. The gas leaks out around the doors (which are not airtight), and in any case would be lost when the water is removed at the surface (with a syringe) for a head-space determination of gas volume and for chemical analysis. This problem has recently been addressed by Kemenes *et al.* (2011). Alexandre Kemenes invented a "Kemenes bottle," which collects the water in a syringe that is lowered to the required depth. The syringe has a spring mechanism that draws in the water for the sample, and the gas bubbles that emerge as the sample is raised to the surface are captured and measured. Comparison of the two sampling methods indicates that the average methane concentration for a sample taken at 30 m depth is 116% higher if measured with the Kemenes bottle, thereby more than doubling the amount of methane estimated to pass through the turbines at Balbina. The difference would be even greater for reservoirs with deeper turbines, as at Tucuruí.

Another important factor affecting the calculated impact of hydroelectric dams is the global warming potential (GWP) of methane. This is the conversion factor for translating tons of methane into tons of CO_2-equivalents. The values for this conversion have increased in successive estimates by the Intergovernmental Panel on Climate Change (IPCC). The conversions are based on the 100-year time horizon adopted by the Kyoto Protocol. The IPCC's 1994 interim report estimated a value of 11 for the GWP of methane, that is, the release of one ton of methane would have the same impact on global warming as releasing 11 tons of CO_2 (Albritton *et al.*, 1995). This was raised to 21 in the 1995 Second Assessment Report used by the Kyoto Protocol (Schimel *et al.*, 1996). In 2001 it was raised to 23 in the Third Assessment Report (Ramaswamy *et al.*, 2001) and then to 25 in the 2007 Fourth Assessment Report (Forster *et al.*, 2007). The Fifth Assessment Report (AR5) increased this to 28 if calculated in the same way (100-year time horizon and no climate-carbon feedbacks in response to CH_4 emissions), but also reports a value of 34 when these feedbacks are included (Myhre *et al*., 2013, p. 714). The uncertainty range for this estimate extends to a value of over 40 (Shindell *et al.*, 2009). The AR5 also reports a value of 86 for the GWP of methane if the time horizon is shortened to 20 years (Myhre *et al*., 2013, p. 714). This shorter time horizon is much more relevant to establishing policies on mitigating global warming, since it is emissions over this period that will determine whether global mean temperature surpasses the limit now agreed as "dangerous": 2°C increase above the pre-industrial mean. As compared to the value of 21 adopted by the Kyoto Protocol for the 2008-2012 First Commitment Period, the value of 34 represents an increase of 62%, whereas the value of 86 effectively quadruples the impact of hydropower. For hydroelectric dams, methane emission represents most of the impact, whereas for fossil fuels almost all of the emission is in the form of CO_2.

Recovery of Methane

Proposals have been made to recover and use some of the methane that is being produced in hydroelectric dams. This would both reduce the amount of methane released to the atmosphere and generate additional electricity without adding to global emissions (Bambace *et al.*, 2007; Lima *et al.*, 2008). One design calls for pumping methane-rich water from below the thermocline **(**Ramos *et al.*, 2009) while another would capture methane that is degassed immediately below the turbines (Kemenes & Forsberg, 2008). So far, no methane-capture system has been implemented in practice.

Comparisons of Dams with Fossil Fuels

The value of time is crucial in comparing the global-warming impact of hydropower and fossil fuels or other energy sources. One difference is the gases emitted. A ton of methane has a very high instantaneous impact in outgoing infrared radiation (increasing surface temperatures), but each molecule only remains in the atmosphere for an average of 12.4 years (Myhre *et al*., 2013, p. 714). A ton of CO_2 blocks much less infrared radiation than a ton of CH_4 on an instantaneous basis, but the average CO_2 molecule remains in the atmosphere for approximately ten times longer than the average CH_4 molecule. This is reflected in the much higher value for methane's GWP on a 20-year basis as compared to a 100-year basis like the GWP that was used by the Kyoto Protocol. Any strategy capable of preventing mean global temperature from surpassing the 2 °C increase limit defining "dangerous" climate change must include reduction of methane emissions within this time period (Shindell *et al*., 2012).

Hydropower has a tremendous emission in the initial years from the death of trees, the underwater decay of soil carbon and of leaves and from the original forest, and the explosion of water weeds in the first years due to the higher fertility of the water. In subsequent years this emission will decline to a lower level that will be maintained indefinitely from renewable sources such as the annual flooding of the soft vegetation in the drawdown zone. The huge peak of emissions in the early years creates a "debt" that will be slowly paid off as power generation from the dam substitutes for fossil-fuel generation over the succeeding years. The time elapsed can be substantial. For example, in the case of Belo Monte plus the first upstream dam (Babaquara/Altamira), the time needed to pay off the initial emission debt is estimated at 41 years (Fearnside, 2009a,b). This is even with the true impact being underestimated by using the Kyoto Protocol value of 21 as the GWP of methane and by using methane concentrations measured with the traditional Ruttner bottles. A period of 41 years has tremendous importance for Amazonia, where the forest itself is under threat from climate changes projected on this time scale (e.g., Fearnside, 2009c). An energy source that takes 41 or more years just to break even in terms of global warming can hardly be considered as "green" energy.

Dams have many other impacts in addition to greenhouse gas emission, including displacement of human populations and loss of livelihoods (for example from fishing) for riverside residents both upstream and downstream of a reservoir (e.g., WCD, 2000). Reservoirs also destroy biodiversity and agricultural and urban land uses. They also provoke methylation of mercury that is present in the soil -- a process occurs in the anoxic conditions at the bottom of reservoirs -- leading to accumulation of this toxic form of mercury in fish and in the humans who consume them. Dams also disrupt sediment flows and fish migrations, among other impacts (see reviews for individual dams in Fearnside, 1989, 1999, 2001, 2005a, 2006b, 2013a, 2014a,b). While other energy sources also have impacts, the social and environmental destruction wrought by dams place this option in a class by itself. In addition, the inordinate concentration of hydropower's impacts on local peoples who happen to live in the path of this form of development represents a social cost that is more pronounced in the case of dams than for other energy options, and that makes the impact of dams even greater than if viewed as a hypothetical "average" spread over society as a whole. The contribution of dams to global warming makes a widely unappreciated addition to these impacts.

Controlling global warming will require an accurate accounting of net emissions throughout the world: any emission that is left out or underestimated implies that mitigation agreements designed to contain temperature rise within a specified limit (such as the 2°C limit currently agreed under the Climate Convention) will simply fail to prevent temperatures from continuing to rise. Amazonia is one of the places expected to suffer the most severe consequences if we fail in this responsibility.

Carbon Credit for Hydropower

Carbon credit that is currently granted to hydropower projects through the Clean Development Mechanism (CDM) is one of the most controversial aspects of efforts to mitigate global warming under the United Nations Framework Convention on Climate Change (UNFCCC). Hydroelectric dams are an increasingly important form of mitigation under the CDM, representing 28% of the expected issuance of credits from projects in the “pipeline” for funding as of 1 July 2014, with an expected annual global total to be granted of 342.8 million certified emissions reductions (CERs), meaning carbon credit expressed as tons of CO_2 equivalent (UNEP Risø Centre, 2014). This amount of CO_2 equivalent is equal to 93.5 million tons of carbon per year, approximately equal to Brazil’s annual emission from fossil fuels. CDM regulations currently allow hydroelectric projects to claim that they produce little or no emissions (see Fearnside, 2013b,c). This represents a significant loophole, especially since much of the future expansion of hydropower is expected to occur in the tropics where dams have the highest emissions. Even more important is the fact that countries throughout the World build dams as part of national development programs that have nothing to do with concerns for global warming. The willingness of governments and companies to invest vast sums in dams long before any carbon credit is approved also indicates that the dams would be built regardless of any additional income from sale of CERs. The financial calculations included in the carbon projects submitted to the CDM to substantiate claims that the dams would only be built because of the carbon income (i.e., that they are “additional”) are at variance with the behavior of the governments and companies building the dams, indicating shortcomings in the CDM’s current methodologies for determining the “addtionality” of hydropower projects (Fearnside, 2013b,c). When credit is granted to projects that would be built anyway, the countries that purchase the credit subsequently emit this amount of CO_2 without the emission actually having been offset, thus further increasing global warming.

CONCLUSIONS

Tropical hydroelectric dams emit substantial amounts of greenhouse gases. The amounts emitted vary greatly among dams, but the reported emissions vary even more due to frequent omissions in the emissions reported, such as methane release from water passing through the turbines and spillways. Hydroelectric emissions occur in a large pulse in the first few years after a reservoir is created, followed by a lower but indefinitely sustained emission. Comparison with the emissions impact of power generation from fossil fuels therefore depends heavily on the time horizon and any weighting for time preference used in the comparison. Even without any weighting for time preference, Amazonian dams can take four or more decades to “break even” in terms of their greenhouse impact, making them anything but “green” energy that can be presented as mitigating global warming. Dams also contribute to global warming through carbon credit issued to dams for which emissions are underestimated or ignored, and by the effect of credit being granted to dams that would be built regardless of any extra income from sale of the credits.

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Figure Legend

Figure 1 – Locations mentioned in the text: 1 = Belo Monte Dam, 2 = Babaquara (Altamira) Dam, 3 = Balbina Dam, 4 = Samuel Dam, 5 = Curuá-Una Dam, 6 = Manso Dam, 7 = Furnas Dam, 8 = Xingó Dam, 9 = Peixoto Dam. 10 = Estreito Dam, 11 = Serra da Mesa Dam, 12 = Tucuruí Dam, 13 = Fortuna Dam, 14 = Petit Saut Dam, 15 = Inambari Dam.