Article

Downstream emissions of CH_4 and CO_2 from hydroelectric reservoirs (Tucuruí, Samuel, and Curuá-Una) in the Amazon basin

Alexandre Kemenes,[1,2] Bruce R. Forsberg,[1] and John M. Melack[3]*

[1] *Instituto Nacional de Pesquisas da Amazonia, Manaus, Brazil*
[2] *Embrapa Meio-Norte, Teresina, Piauí, Brazil*
[3] *Bren School of Environmental Science and Management, University of California, Santa Barbara, CA, USA*
**Corresponding author: john.melack@lifesci.ucsb.edu*

Received 16 February 2016; accepted 15 March 2016; published 27 May 2016

Abstract

Carbon dioxide (CO_2) and methane (CH_4) generated in reservoirs are released downstream of dams, and few studies have considered these downstream emissions. Fluxes downstream of 3 Amazon hydroelectric reservoirs (Tucuruí, Samuel, and Curuá-Una) are reported here. Degassing through turbines was calculated as the difference between intake and outflow concentrations. Additional releases along the Tocantins, Jamari, and Curuá rivers were measured at downstream sites over a distance of 30 km. About 50% of the CH_4 and 30% of the CO_2 emitted downstream of the dam were liberated at the turbine outflow. The total downstream emissions are sufficiently large to require consideration in assessments of greenhouse gas emissions from hydroelectric reservoirs.

Key words: Amazon reservoirs, carbon dioxide, downstream emission, hydroelectric dams, methane

Introduction

As the significant role of inland waters in the global carbon cycle has become evident (Cole et al. 2007, Aufdenkampe et al. 2011, Raymond et al. 2013), the potential for reservoirs, especially in tropical regions, to contribute to increases in carbon dioxide (CO_2) and methane (CH_4) in the atmosphere has become increasingly apparent (Saint Louis et al. 2000, Fearnside and Pueyo 2012). High rates of autotrophic and heterotrophic processes in the tropics often lead to waters supersaturated in CO_2 and CH_4 and large evasion of these greenhouse gases (GHG; Richey et al. 2002, Melack et al. 2004, Melack 2016). Ebullitive gas release below hydroelectric turbines and outgassing further downstream contribute to emissions from tropical reservoirs (Abril et al. 2005, Guerin et al. 2006, Kemenes et al. 2007, 2011). As construction of tropical hydroelectric reservoirs continues, their contribution to atmospheric levels of GHG is likely to increase (Tucci et al. 2009, Faria et al. 2015).

Degradation of organic matter under oxic and anoxic conditions generates CO_2, whereas CH_4 is produced under anaerobic conditions (Bridgham et al. 2013, Schlesinger and Bernhardt 2013). The organic matter fueling these processes in reservoirs is derived from carbon fixed within the water and from material transported from the surrounding watershed. Exchange of CO_2 and CH_4 between surficial water and overlying atmosphere depends on the concentration gradient between air and water and on physical processes at the interface (MacIntyre et al. 1995). Outgassing of CH_4 can be enhanced by ebullition and passage through plant stems and reduced via CH_4 oxidation by methanotrophic bacteria.

Several studies have reported that tropical reservoirs emit CH_4 and CO_2 to the atmosphere (Galy-Lacaux et al. 1999, Duchemin et al. 2000, Lima et al. 2002, Abril et al. 2005, Guerin et al. 2006, Kemenes et al. 2007, 2011, Ometto et al. 2013). Few of these studies, however, have measured CH_4 and CO_2 released by degassing through turbines or emitted by downstream rivers. Hence, downstream emissions are underestimated or ignored by regional estimates and national CH_4 and CO_2 inventories (Barros et al. 2011, Bastviken et al. 2011, Fearnside and Pueyo 2012). Reservoirs worldwide stratify thermally and accumulate high concentrations of CH_4 and CO_2 at depth; this phenomenon is particularly acute in tropical reservoirs. The drop in hydrostatic pressure that occurs as bottom

DOI: 10.5268/IW-6.3.980

waters pass through turbines can result in large releases of dissolved gases to the atmosphere. The pressure drop affects these gases differently; because CH_4 is less soluble in water than CO_2, it is more vulnerable to pressure changes. The CH_4 and CO_2 that remain in solution below the turbine outflow are released gradually to the atmosphere in the downstream river channel.

In Brazil, hydropower represents more than 80% of the country's supply of electricity (EPE 2012), and several hydroelectric reservoirs have been built or will be built in tropical forests with large carbon stocks (Malhi and Phillips 2004, Faria et al. 2015). After impoundment, this organic matter decomposes, creating elevated concentrations and fluxes of CH_4 and CO_2 to the atmosphere. Inflows and primary production within the reservoirs supply additional organic matter that sustain releases of CH_4 and CO_2. Twenty years after the formation of Balbina Reservoir in the central Amazon basin, considerable amounts of CH_4 and CO_2 continued to be emitted to the atmosphere, and a significant part of these emissions occurred downstream of the dam (Kemenes et al. 2007, 2011). Downstream emissions from other Amazonian reservoirs may also be important but are insufficiently characterized.

Our objective was to report measurements of CH_4 and CO_2 fluxes made downstream of 3 Amazon hydroelectric dams (Tucuruí, Samuel, and Curuá-Una) and to compare and discuss them in the context of total CH_4 and CO_2 emissions from these and other reservoirs. Our results contribute to understanding of the role of inland waters in carbon cycling and have relevance to CH_4 and CO_2 inventories for Brazil and other tropical countries. The evaluation of environmental impacts of planned and current hydroelectric reservoirs in the Amazon basin and elsewhere will benefit from our findings.

Study sites

During 2008 and 2009, Tucuruí, Samuel, and Curuá-Una hydroelectric reservoirs were sampled (Fig. 1). The Tucuruí dam on the Tocantins River was completed in 1984 and formed a reservoir with an average area of ~1850 km^2 and an energy potential of 8085 MW (Eletronorte, unpublished data). Only 8% of the flooded area was deforested, and decomposition of the large submerged carbon stock has resulted in significant GHG emissions (Lima et al. 2002). Samuel Reservoir on the Jamari River, 50 km above Porto Velho (Rondônia), inundates about 550 km^2, is 30 years old, and started producing energy in 1996. Its maximum hydroelectric power potential is about 220 MW, but maximum generation is only achieved during a few months each year (Lima et al. 2002). Curuá-Una Reservoir, created on the Curuá-Una River 70 km from Santarem (Pará) in 1977, covers about 70 km^2 and has 40 MW of power potential (Fearnside 2005).

During our study, water levels at Tucuruí varied about 12 m upstream and 8 m downstream of the dam. At Samuel, the variation was 8 m upstream and 5 m downstream, and Curuá-Una varied between 3 and 5 m upstream and downstream, respectively. The average depths of the turbine intakes were about 50, 40, and 15 m in Tucuruí, Samuel, and Curuá-Una reservoirs, respectively. The fluxes of water through the turbines were about 9300, 590, and 190 m^3 s^{-1} in the rainy season (mean values for Tucuruí and Curuá-Una from November to April and for Samuel from January to June) and ~6800, 260, and 80 m^3 s^{-1} in the dry season (mean values for Tucuruí and Curuá-Una from May to October and for Samuel from July to December) in Tucuruí, Samuel, and Curuá-Una, respectively (Eletronorte, unpublished data). All 3 reservoirs' waters are dilute (conductances vary from 6 to 10 μS cm^{-1}) with near neutral pH (6.0–7.4) and dissolved organic carbon concentrations ranging from 2.7 to 7.1 mg L^{-1} (Eletronorte, unpublished data).

Power density is used to classify hydroelectric systems under the framework of the Kyoto Protocol's Clean Development Mechanism (CDM), using potential energy (MW) per inundated area (km^2) for the calculation. Carbon credits, as determined by certified emissions reductions, are regulated by the United Nations Framework Convention on Climate Change. Hydroelectric power plants with power densities >10 MW km^{-2} automatically receive carbon credits. Power plants with power densities >4 MW km^{-2} but ≤10 MW km^{-2} are eligible to apply as CDM projects, but only with mean emissions from 100 to 90 gCO_2 eq kW h^{-1}. Systems producing <4 MW km^{-2} cannot receive environmental credits. In the Amazon, Balbina has the lowest energetic density (0.09 MW km^{-2}); Tucuruí has a power density of 3.6 MW km^{-2}, Samuel of ~0.6 MW km^{-2}, and Curuá-Una of 0.8 MW km^{-2}. If they were built today, none of these reservoirs would be eligible for carbon credits.

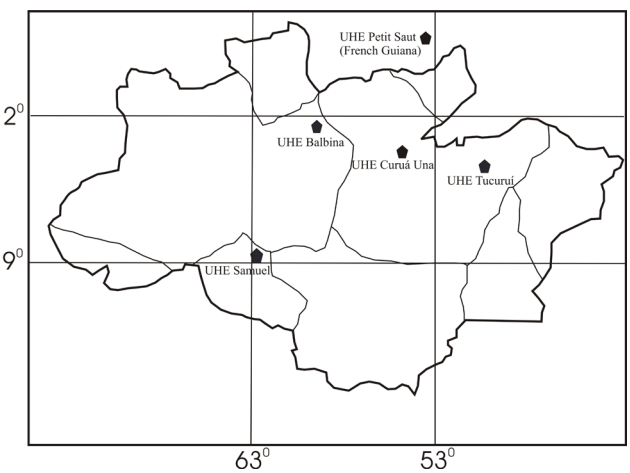

Fig. 1. Amazon hydroelectric reservoirs (Tucuruí, Samuel, Curuá-Una, and Balbina, plus Petit Saut French Guiana). Outline denotes Amazon basin.

 DOI: 10.5268/IW-6.3.980

Table 1. The ranges of CH_4 and CO_2 surficial and bottom concentrations (μM) measured in Tucuruí, Samuel, and Curuá-Una reservoirs between April 2008 and January 2009.

	Tucuruí		Samuel		Curuá-Una	
	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2
Minimum surficial concentration	0.12	124	0.25	77	0.13	82
Maximum surficial concentration	0.41	412	0.6	214	0.27	373
Minimum near-bottom concentration	3.6	248	2.6	290	1.3	274
Maximum near-bottom concentration	222	965	16.6	661	11.5	662

Methods

Field measurements and collections were made in April, June, and September 2008 and January 2009. Dissolved oxygen and temperature profiles were determined in the reservoirs near the dams and in the near-surface water of the downstream rivers with a polarographic electrode and thermistor (YSI model 85). The transparency of water was estimated with a 20 cm Secchi disk. Measurements were made in the downstream rivers below the dam at 7 points: 50 m, 5 km, 10 km, 15 km, 20 km, 25 km, and 30 km. Daily values of turbine discharge, reservoir stage, and rainfall were provided for each reservoir by Eletronorte (unpublished data).

Duplicate samples of dissolved gases were taken in the reservoirs just above the dams at a series of depths beginning at the surface (Samuel and Tucuruí every 10 m and Curuá Una every 5 m) and in the downstream rivers just below the dams and at 5 km intervals for 30 km below the dams. Water samples near the turbine inflow were collected upstream of the dam using a sampler (described in Kemenes et al. 2011) consisting of a weighted housing that secures a 60 mL polyethylene syringe in a vertical position. Before lowering, a solenoid valve at the mouth of the syringe was closed and a vacuum applied to the syringe by securing it in an extended position. At the sample depth, the solenoid valve was opened to collect the sample. The sampler and syringe were maintained in a vertical position during retrieval to ensure that gas bubbles released during the process were retained in the syringe. At the surface, the syringe was treated by the headspace method (Johnson et al. 1990), ensuring that both the equilibrated gas and any released bubbles were included in the final gas sample.

Emission measurements of CH_4 and CO_2 in the rivers were made with drifting chambers, as described in Kemenes et al. (2011). The 0.23 m^2 floating chamber was covered with reflective insulation and equipped with an internal fan to improve circulation and maintain ambient temperature; the lower 3 cm of the chamber wall was submersed during deployment. During each measurement, 4 gas samples were collected from the chamber at 5-minute intervals with 60 mL polyethylene syringes and stored in 20 mL glass serum vials with high density butyl rubber stoppers until analysis. All measurements were made in duplicate. CH_4 and CO_2 were determined using a dual column gas chromatograph and methodology described by Hamilton et al. (1995). Standard gases (CO_2: 300 and 900 ppmv; CH_4: 0.8 and 3.6 ppmv) were used routinely during analyses.

CH_4 and CO_2 discharges through the turbines were estimated using daily water discharges and gas concentrations interpolated between measurement dates. Daily emission for each river reach between sampling sites was estimated from the product of the area of the reach and the areal emission rate. Widths of each 5 km reach were calculated from a Landsat TM satellite image.

The difference between the downstream CH_4 discharges (daily water discharge × CH_4 concentration) at the beginning and end of each reach was used to estimate the total daily loss of CH_4. CH_4 oxidation along each reach was estimated as the difference between the total daily CH_4 loss and the diffusive emission, assuming no ebullitive losses in river. The final results are in C as CO_2 yr^{-1}. CH_4 emissions were normalized using a 100-year global warming factor of 34 $kgCO_2/kgCH_4$ (Myhre et al. 2013).

Results

Average near-surface water temperatures were 28.5, 28.3, and 28.5 °C during the rainy season and 29.5, 30.8, and 30.4 °C during the dry season, whereas near-bottom reservoir temperatures were 26.8, 27.1, and 28.5 °C during the rainy season and 28.1, 29.6, and 29.5 °C during the dry season in Tucuruí, Samuel, and Curuá-Una reservoirs, respectively (near-surface and near-bottom refer to the top and bottom of the profiles in Fig. 2). Oxyclines were located ~50, 40, and 15 m in Tucuruí, Samuel, and Curuá-Una, respectively, with hypoxic hypolimnia below those depths. Near-surface oxygen concentrations ranged from 0.15, 0.11, and 0.13 mM to 0.18, 0.22, and 0.15 mM, whereas near-bottom concentrations varied from 0.02, 0.06, and 0.09 mM to 0.09, 0.11, and 0.13 mM in Tucuruí, Samuel, and Curuá-Una, respectively (Fig. 2). Maximum dissolved oxygen was recorded in January and minimum in September. CH_4 and CO_2 concentrations were relatively low near the surface and increased with depth (Fig. 2, Table 1); average surface concentrations of CO_2 at the dams were 273, 303, and 525 μM in Tucuruí, Samuel, and Curuá-Una, respectively.

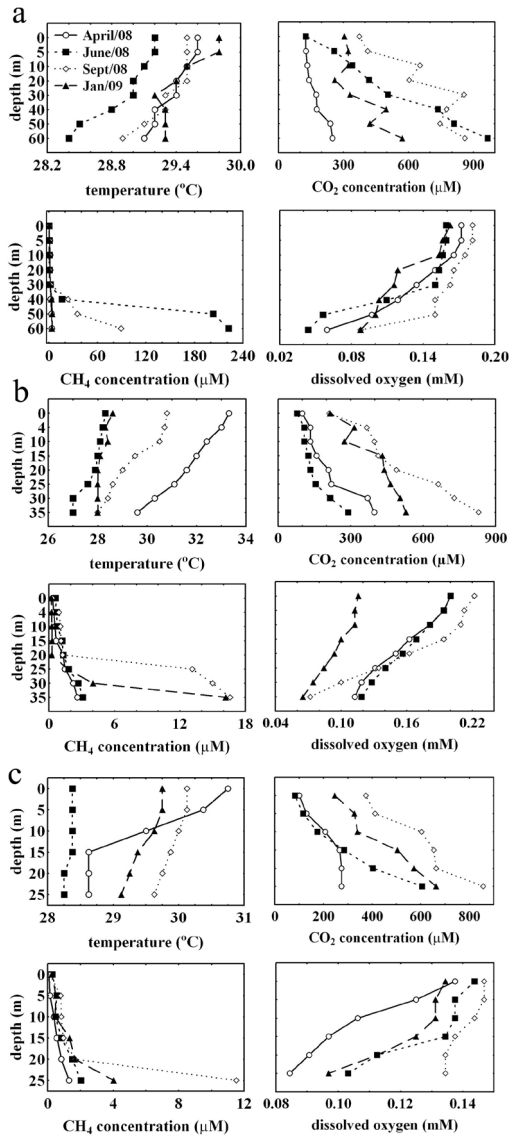

Fig. 2. Vertical profiles of temperature and concentrations of CH_4, CO_2, and dissolved oxygen in (a) Tucuruí, (b) Samuel, and (c) Curuá-Una reservoirs upstream of the turbines near the dams. Data were collected between April 2008 and January 2009.

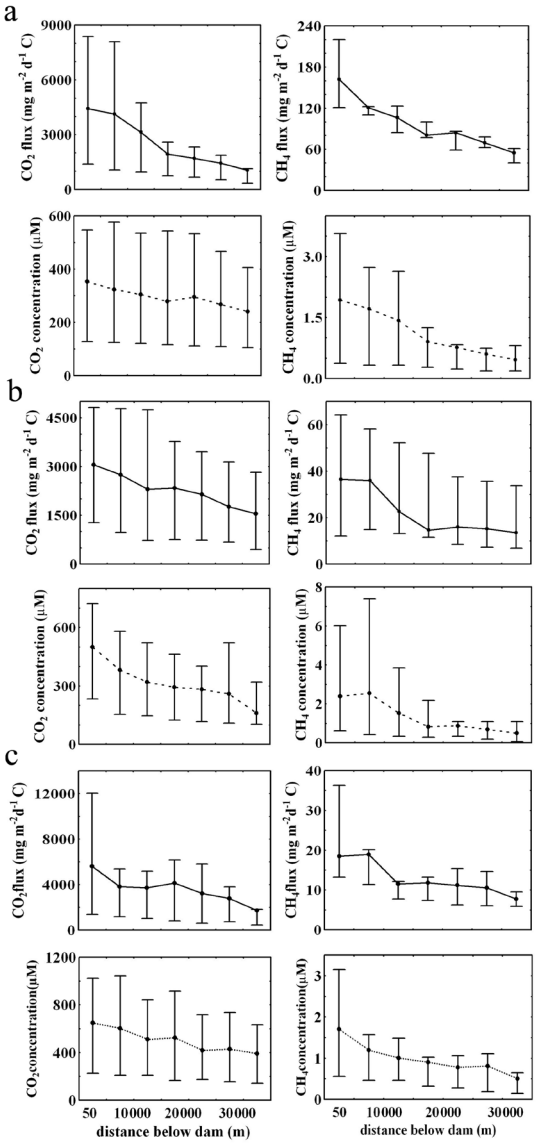

Fig. 4. Variation in the surface concentration and emission of CH_4 and CO_2 along the (a) Tocantins, (b) Jamari, and (c) Curuá rivers downstream from their respective dams. Annual means and ranges are shown. Data were collected between April 2008 and January 2009.

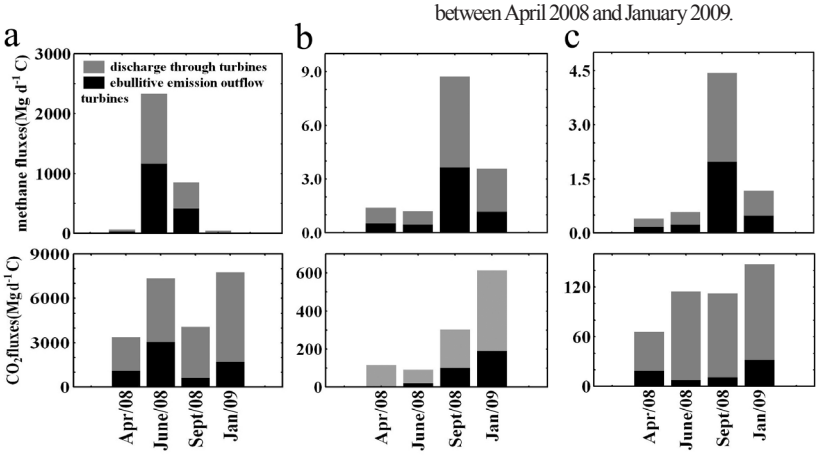

Fig. 3. Seasonal variation in water discharge and degassing at the turbine outflow of (a) Tucuruí, (b) Samuel, and (c) Curuá-Una dams.

DOI: 10.5268/IW-6.3.980

Table 2. Annual CO_2 and CH_4 fluxes (Gg yr^{-1} of C) below Tucuruí, Samuel, and Curuá-Una dams.

Hydroelectric dams	Tucuruí		Samuel		Curuá-Una	
	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2
Degassing at the turbine outflow	165	943	1.3	25	0.26	7.9
Residual fluxes at the turbine outflow (passing through turbines)	6	879	0.3	52	0.08	27
Emission from river channel for first 30 km reach below dam	4	55	0.1	14	0.03	12
Residual fluxes at 30 km	2	824	0.2	38	0.05	15
Total discharge through turbines	171	1822	1.6	77	0.34	33
Total emission below dam for 30 km	169	998	1.4	39	0.29	19.9

The average concentrations of CH_4 and CO_2 measured above (turbine intake) and below (turbine outflow) at Tucuruí, Samuel, and Curuá-Una dams indicate a significant decrease at the outflow (Table 2). The lowest values occurred during the rainy season (Jan, Mar, Apr) and higher values occurred in the dry season (Jun, Jul, Aug). Degassing of CH_4 and CO_2 at the turbine outflow, expressed as CO_2 equivalents C (CO_2-C), was estimated as ~2400 Gg yr^{-1} (Tucuruí), ~35 Gg yr^{-1} (Samuel), and ~10 Gg yr^{-1} (Curuá-Una; Fig. 3). About 71, 69, and 45% of the gases passing through the turbines were lost to atmosphere at Tucuruí, Samuel, and Curuá-Una, respectively. The degassing of CO_2 from Tucuruí, Samuel, and Curuá-Una turbines averaged ~52, 34, and 21% of the total turbine discharge, whereas degassing of CH_4 at the turbine outflow accounted, on average, for 81, 73, and 72% of total turbines discharge (Fig. 3).

The residual discharge of dissolved CH_4 and CO_2 not degassing at the turbines was transported and gradually emitted to the atmosphere downstream. The average surface concentrations of CH_4 along the 30 km reach below Tucuruí, Samuel, and Curuá-Una dams were 1.3, 1.5, and 1.1 µM, and the average C emissions were 102, 19.8, and 13.2 mg m^{-2} d^{-1}, respectively (Fig. 4).

Emissions integrated along the 30 km downstream reaches varied seasonally (Fig. 5). In 2009, the total fluxes of CH_4 and CO_2 in 30 km of the Tocantins, Jamari, and Curuá rivers downstream of Tucuruí, Samuel, and Curuá-Una dams were ~131 Gg yr^{-1} CO_2-C (CH_4 represents ~ 31% of this value).

Discussion

In stratified reservoirs, the bottom stratum enters the turbines from the lower layers with elevated hydrostatic pressure (Ivey and Imberger 1978, Hocking et al. 1988, Thornton et al. 1990) and high gas concentrations (Kemenes et al. 2007, 2011). The deep inlets to the turbines in Tucuruí, Samuel, and Curuá-Una dams carry pressurized water supersaturated with CH_4 and CO_2. As a result, enhanced outgassing occurs and represents an important route of CO_2 and CH_4 to the atmosphere.

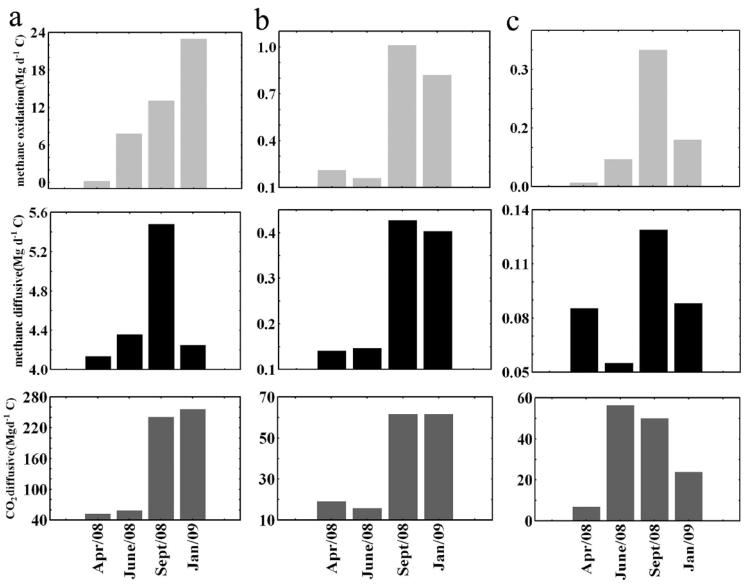

Fig. 5. Seasonal variation of diffusive CH_4 and CO_2 emissions and CH_4 oxidation losses in the (a) Tocantins, (b) Jamari, and (c) Curuá rivers, downstream of Tucuruí, Samuel, and Curuá-Una dams, respectively. Data were collected between April 2008 and January 2009.

Table 3. Total annual greenhouse gas releases downstream from Amazon hydroelectric dams. All fluxes are in Gg yr^{-1} of C.

	Tucurui		Samuel		Curuá-Una		Balbina[a]	
	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2
Downstream dam	169	998	1.5	39	0.3	20	39	81

[a] Kemenes et al. 2007, 2011

We compared our results with available seasonal data, including downstream emissions, from 2 other reservoirs with tropical forest watersheds in or near the Amazon basin. In Balbina Reservoir, near-bottom CH_4 concentrations varied between 17 and 696 µM with a mean value of 168 µM, and surficial concentrations varied between 0.1 and 3.9 µM with a mean of 1.6 µM (Kemenes et al. 2007); near-bottom CO_2 concentrations varied between 52 and 375 µM with a mean of 161 µM, and surficial concentrations varied between 42 and 180 µM with a mean of 99 µM (Kemenes et al. 2011). In Petit-Saut Reservoir, near-bottom CH_4 and CO_2 concentrations varied from 0.3 to 1300 µM and 157 to 1516 µM with means of 300 and 475 µM, respectively. Surface CH_4 and CO_2 concentrations varied from 0.1 to 275 µM and 4 to 773 µM with mean values of 24 and 140 µM, respectively (Abril et al. 2005).

Downstream of Balbina dam in the Uatumã River, the average concentration of CH_4 was 36 µM and the average C emission was 1690 mg m^{-2} d^{-1} (Kemenes et al. 2007), a value similar to that found by Guerin et al. (2006) during a single campaign in 2004 (1370 mg m^{-2} d^{-1}). The average concentration of CO_2 below Balbina dam was 161 µM and the average C emission was 4790 mg m^{-2} d^{-1} (Kemenes et al. 2011). CH_4 fluxes in the Sinnamary River below Petit Saut Dam averaged 1050 mg m^{-2} d^{-1} of C, and CO_2 fluxes averaged 11 400 mg m^{-2} d^{-1} of C (Abril et al. 2005). CO_2 and CH_4 concentrations and the fluxes declined downstream of dams in all rivers, despite additional inputs of gases from tributaries, floodplains, and CH_4 oxidation.

At Balbina, ~53% of the CH_4 that passed through the turbines was lost to the atmosphere (Kemenes et al. 2007). Degassing below the Petit-Saut dam was more efficient, accounting for ~80% of the annual CH_4 discharge. The large ebullitive CH_4 loss at Petit-Saut can be attributed to a weir installed immediately below the dam to improve oxygenation and reduce the fish mortality (Abril et al. 2005). At Balbina, about 51% of the downstream emission of CO_2 was released by degassing at the turbines, and the remainder was lost downstream in the Uatumã River; at Petit-Saut 18% was degassed at the turbines (Abril et al. 2005, Kemenes et al. 2011).

The variability among dams in the percentage of total emissions released at the turbine outflow is probably due to differences in design. The average depth of the water column determines the hydrostatic pressure and the proportion of the CH_4 oxidized to CO_2, which, depending on the depth of the intake, could affect degassing at the outflow (Kemenes et al. 2011). In addition, CH_4 flux downstream of the dams had seasonal variation. The lowest fluxes were found in the rainy season when the reservoir was weakly stratified and the CH_4 concentrations were low in the hypolimnion (Kemenes et al. 2007). Another source of variability is likely due to differences in the methods used to obtain gas samples (Kemenes et al. 2011).

Total annual emissions downstream from Tucuruí, Samuel, Curuá-Una, and Balbina dams, including both turbine degassing and downstream diffusion, were summarized (Table 3). The large differences in total downstream emission between dams are presumably related to the size of the dams and the energy capacity of their turbines. The larger the energy capacity, the more hypolimnetic reservoir water is expected to pass through the turbines, resulting in higher levels of degassing and downstream diffusive losses. Strong positive correlations were encountered between total downstream emissions and energy capacity (MW) for both CO_2 (r = 0,999, $p < 0.007$) and CH_4 (r = 0.977, $p < 0.02$) for the dams (Table 3). The data distribution was too clustered to develop a robust regression model. As more data on downstream emissions become available, predictive relationships can be developed, allowing estimation of downstream emission in both existing and future dams directly from their energy capacity.

In 2005, the total surficial flux of CH_4 and CO_2 in the Uatumã River downstream Balbina Dam was ~103 Gg yr^{-1} of CO_2-C (CH_4: 5 Gg yr^{-1} of C; CO_2: 41 Gg yr−1 of C; Kemenes et al. 2007, 2011). At Petit-Saut, total surficial GHG flux in the Sinnamary River downstream of the dam was ~111 yr^{-1} of CO_2-C (Abril et al. 2005).

Together, the Amazon hydroelectric reservoirs discussed here (Tucuruí, Samuel, and Curuá-Una) plus Balbina emit about 0.21 Tg yr^{-1} of C as CH_4 and 1.14 Tg yr^{-1} of C as CO_2 downstream of the dams (Table 3). CH_4 emissions from the surface of Balbina Reservoir were estimated to be 34 Gg yr^{-1} of C, indicating the importance of downstream measurements (55% of total emissions). Similarly, downstream emissions at Petit Saut Reservoir accounted for 57% of total CH_4 emissions during a 10-year period (Abril et al. 2005). None of the other tropical reservoirs in South America has sufficient data on upstream turbine releases or downstream river emissions to allow these calculations.

 DOI: 10.5268/IW-6.3.980

To evaluate the net contribution of reservoirs to climate warming, the carbon balance of the ecosystem that existed in the region of the reservoirs before impoundment must be considered. If that system was a net source of GHGs, its emission would have to be subtracted from that estimated here. If the system was a net sink for these gases, however, the pre-inundation sequestration rate would have to be added to our emission estimate. The river reaches and their associated narrow floodplains in the area now occupied by the reservoirs were presumably net sources of both CO_2 and CH_4, as has been demonstrated for most rivers and floodplains in the Brazilian Amazon (Richey et al. 2002, Melack et al. 2004). These features occupied only a small fraction of the reservoir area, however, and presumably had a small effect on the regional carbon balance. Most of the regions were occupied by upland tropical broadleaf forest, an ecosystem shown to be a net sink for both CO_2 and CH_4 in several studies (Steudler et al. 1996, Verchot et al. 2000, Malhi and Phillips 2004). Assuming that carbon dynamics in the upland forest dominated the mass balance of CO_2 and CH_4, the regions currently occupied by the reservoir were probably originally a net sink for these gases, and the estimates presented here likely underestimate the contributions of hydroelectric systems to atmospheric warming. All Amazon hydroelectric systems studied release considerable amounts of CO_2 and CH_4 to the atmosphere (Duchemin et al. 2000, Lima et al. 2002, Abril et al. 2005, Kemenes et al. 2007, 2011). As Brazil expands its network of hydroelectric systems in regions with tropical forests, their contribution to the national inventory of GHGs will need to be considered.

Acknowledgements

We thank NASA's LBA-ECO program for funding, CAPES/CNPq for fellowship support, and Electronorte for permission to sample the reservoirs and rivers and for logistical support and data.

References

Abril G, Guerin F, Richard S, Delmas R, Galy-Lacaux C, Gosse P, Tremblay A, Varfalvy L, Santos MA, Matvienko B. 2005. Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana). Glob Biogeochem Cy. 19:1–16.

Aufdenkampe AK, Mayorga E, Raymond PA, Melack JM, Doney SC, Alin SR, Aalto RE, Yoo K. 2011. Rivers key to coupling biogeochemical cycles between land, oceans and atmosphere. Front Ecol Environ. 9:53–60.

Barros N, Cole JJ, Tranvik LJ, Prairie YT, Bastviken D, Huszar VLM, Del Giorgio P, Roland F. 2011. Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. Nature Geosci Lett. 4:593–596.

Bastviken D, Tranvik LJ, Downing JA, Crill PM, Enrich-Prast A. 2011. Freshwater methane emissions offset the continental carbon sink. Science. 331:50.

Bridgham S, Cadillo-Quiroz H, Kazahaya K, Zhuang Q. 2013. Methane emissions from wetlands: biogeochemical, microbial, and modeling perspectives from local to global scales. Global Change Biol. 19:1325–1346.

Cole JJ, Praire YT, Caraco NF, McDowell WH, Tranvik LJ, Striegl RR, Duarte CM, Kortelainen P, Downing JA, Middleburg J, Melack JM. 2007. Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget. Ecosystems. doi:10.1007/s10021-006-9013-8

Duchemin E, Lucotte M, Canuel R, Queiroz AG, Almeida DC, Pereira HC, Dezincourt J. 2000. Comparison of greenhouse gas emissions from an old tropical reservoir with those of 355 other reservoirs worldwide. Verh Internat Verein Limnol. 27:1391–1395.

[EPE] Empresa de Pesquisa Energética. 2012. Balanço Energético Nacional 2012. Brasília (DF).

Faria FAM, Jaramillo P, Sawakuchi HO, Richey JE, Barros N. 2015. Estimating greenhouse gas emissions from future Amazonian hydroelectric reservoirs. Environ Res Lett. doi:10.1088/1748-9326/10/12/124019

Fearnside PM. 2005. Do hydroelectric dams mitigate global warming? The case of Brazil's Curuá-Una Dam. Mitigation and Adaptation Strategies for Global Change. 10:675–691.

Fearnside PM, Pueyo S. 2012. Greenhouse gas emissions from tropical dams. Nature Clim Change. 2:1–3.

Galy-Lacaux C, Delmas R, Kouadio G, Richard S, Gosse P. 1999. Long-term greenhouse gas emissions from hydroelectric reservoirs in tropical forest regions. Global Biogeochem Cy. 13:503–517.

Guerin F, Abril G, Richard S, Burban B, Reynouard C, Seyler P, Delmas R. 2006. Methane and carbon dioxide emissions from tropical reservoirs: significance of downstream rivers. Geophys Res Lett. 33:1–6.

Hamilton SK, Sippel SJ, Melack JM. 1995. Oxygen depletion, carbon dioxide and methane production in waters of Pantanal wetland of Brazil. Biogeochemistry. 30:115–141.

Hocking GC, Sherman BS, Patterson JC. 1988. Algorithm for selective withdrawal from a stratified reservoir. J Hydraul Div. 114:707–719.

Ivey GN, Imberger J. 1978. Field investigation of selective withdrawal. J Hydraul Div. 104:1225–1237.

Johnson KM, Hughes JE, Donaghay PL, Sieburth JM. 1990. Bottle-calibration static headspace method for determination of methane dissolved in seawater. Anal Chem. 62:2408–2412.

Kemenes A, Forsberg BR, Melack JM. 2007. Methane release below a tropical hydroelectric dam. Geophys Res Lett. 34:L12809. doi:10.1029/2007GL029479

Kemenes A, Forsberg BR, Melack JM. 2011. CO_2 emissions from a tropical hydroelectric reservoir (Balbina, Brazil). J Geophys Res. 116:G03004. doi:10.1029/2010JG001465

Lima IBT, Victoria RL, Novo EMLM, Freigl BJ, Ballester MVR, Ometto JP. 2002. Methane, carbon dioxide and nitrous oxide

emissions from two Amazonian reservoirs during high water table. Verh Internat Verein Limnol. 28:438–442.

MacIntyre S, Wanninkhof R, Chanton J. 1995. Trace gas exchange across the air–water interface in freshwater and coastal marine environments. In: Matson P, Harriss R, editors. Biogenic trace gases: measuring emissions from soil and water. Oxford (UK): Blackwell. p. 52–97.

Malhi Y, Phillips O. 2004. Tropical forests and global atmospheric change: a synthesis. Phil Trans R Soc. doi:10.1098/rstb.2003.1449

Melack JM. Forthcoming 2016. Aquatic ecosystems. In: Nagy L, Forsberg BR, Artaxo P, editors. The large-scale biosphere atmosphere programme in Amazonia. Ecological studies. New York (NY): Springer.

Melack JM, Hess LL, Gastil M, Forsberg BR, Hamilton SK, Lima IBT, Novo EMLM. 2004. Regionalization of methane emission in the Amazon Basin with microwave remote sensing. Global Change Biol. 10:530–544.

Myhre G, Shindell D, Breon FM, Collins W, Fuglestvedt J, Huang J, Koch D, Lamarque JF, Lee D, Mendoza B, Nakajima T, et al. 2013. Anthropogenic and natural radiative forcing. In: Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge (UK) and New York (NY): Cambridge University Press.

Ometto JP, Cimbleris ACP, Santos MA, Rosa LP, Abe D, Tundisi JG, Stech JL, Barros N, Roland F. 2013. Carbon emission as a function of energy production in hydroelectric reservoirs in Brazilian dry tropical biome. Energy Policy. 58:109–116.

Raymond PA, Hartmann J, Lauerwald R, Sobek S, McDonald C, Hoover M, Butman D, Striegl R, Mayorga E, Humborg C, et al. 2013. Global carbon dioxide emissions from inland waters. Nature. 503:355–359.

Richey JE, Melack JM, Aufdenkampe K, Ballester VM, Hess LL. 2002. Outgassing from Amazonian rivers and wetlands as a large tropical source at atmospheric CO_2. Nature. 416:17–620.

Saint Louis VC, Kelly C, Duchemin E, Rudd JWM, D.M. Rosenberg DM. 2002. Reservoir surface as sources of greenhouse gases to the atmosphere: a global estimate. Bioscience. 20:766–775.

Schlesinger WH, Bernhardt ES. 2013. Biogeochemistry. Cambridge (MA): Elsevier.

Steudler PA, Melillo JM, Feigl BJ. 1996. Consequence of forest-to-pasture conversion on CH_4 fluxes in the Brazilian Amazon. J Geophys Res. 101:18547–18554.

Thornton KW, Kimmel BL, Payne FE. 1990. Reservoir limnology: ecological perspectives. New York (NY): John Wiley & Sons.

Tucci C, Taylor R, Harby A, Melack JM, editors. 2009. Assessment of the GHG status of freshwater reservoirs. Paris (France): UNESCO.

Verchot LV, Davidson EA, Cattânio JH. 2000. Land use change and biogeochemical controls of methane fluxes in soils in eastern Amazonia. Ecosystems. 3:41–56.

 DOI: 10.5268/IW-6.3.980