Downstream emissions of CH\textsubscript{4} and CO\textsubscript{2} from hydroelectric reservoirs (Tucuruí, Samuel, and Curuá-Una) in the Amazon basin

Alexandre Kemenes\textsuperscript{1,2}, Bruce R. Forsberg\textsuperscript{1}, and John M. Melack\textsuperscript{3*}

\textsuperscript{1}Instituto Nacional de Pesquisas da Amazônia, Manaus, Brazil
\textsuperscript{2}Embrapa Meio-Norte, Teresina, Piauí, Brazil
\textsuperscript{3}Bren School of Environmental Science and Management, University of California, Santa Barbara, CA, USA

*Corresponding author: john.melack@lifesci.ucsb.edu

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Abstract

Carbon dioxide (CO\textsubscript{2}) and methane (CH\textsubscript{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\textsubscript{4} and 30\% of the CO\textsubscript{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\textsubscript{2}) and methane (CH\textsubscript{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\textsubscript{2} and CH\textsubscript{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\textsubscript{2}, whereas CH\textsubscript{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\textsubscript{2} and CH\textsubscript{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\textsubscript{4} can be enhanced by ebullition and passage through plant stems and reduced via CH\textsubscript{4} oxidation by methanotrophic bacteria.

Several studies have reported that tropical reservoirs emit CH\textsubscript{4} and CO\textsubscript{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\textsubscript{4} and CO\textsubscript{2} released by degassing through turbines or emitted by downstream rivers. Hence, downstream emissions are underestimated or ignored by regional estimates and national CH\textsubscript{4} and CO\textsubscript{2} inventories (Barros et al. 2011, Bastviken et al. 2011, Fearnside and Pueyo 2012). Reservoirs worldwide stratify thermally and accumulate high concentrations of CH\textsubscript{4} and CO\textsubscript{2} at depth; this phenomenon is particularly acute in tropical reservoirs. The drop in hydrostatic pressure that occurs as bottom...
winters pass through turbines can result in large releases of dissolved gases to the atmosphere. The pressure drop affects these gases differently; because CH₄ is less soluble in water than CO₂, it is more vulnerable to pressure changes. The CH₄ and CO₂ 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 CH₄ and CO₂ to the atmosphere. Inflows and primary production within the reservoirs supply additional organic matter that sustain releases of CH₄ and CO₂. Twenty years after the formation of Balbina Reservoir in the central Amazon basin, considerable amounts of CH₄ and CO₂ 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 CH₄ and CO₂ fluxes made downstream of 3 Amazon hydroelectric dams (Tucuruí, Samuel, and Curuá-Una) and to compare and discuss them in the context of total CH₄ and CO₂ emissions from these and other reservoirs. Our results contribute to understanding of the role of inland waters in carbon cycling and have relevance to CH₄ and CO₂ 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 km² 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 km², 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 km² and has 40 MW of power potential (Fearnside 2005).

During our study, water levels at Tucurui 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 Tucurui, Samuel, and Curuá-Una reservoirs, respectively. The fluxes of water through the turbines were about 9300, 590, and 190 m³ s⁻¹ in the rainy season (mean values for Tucurui and Curuá-Una from November to April and for Samuel from January to June) and ~6800, 260, and 80 m³ s⁻¹ in the dry season (mean values for Tucurui and Curuá-Una from May to October and for Samuel from July to December) in Tucurui, 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 (km²) 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 gCO₂ 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.](image-url)
Table 1. The ranges of CH$_4$ and CO$_2$ surficial and bottom concentrations (µM) measured in Tucurui, Samuel, and Curuá-Una reservoirs between April 2008 and January 2009.

<table>
<thead>
<tr>
<th></th>
<th>Tucurui</th>
<th>Samuel</th>
<th>Curuá-Una</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum surficial concentration</td>
<td>0.12</td>
<td>0.25</td>
<td>0.13</td>
</tr>
<tr>
<td>Maximum surficial concentration</td>
<td>0.41</td>
<td>0.6</td>
<td>0.27</td>
</tr>
<tr>
<td>Minimum near-bottom concentration</td>
<td>3.6</td>
<td>2.6</td>
<td>1.3</td>
</tr>
<tr>
<td>Maximum near-bottom concentration</td>
<td>222</td>
<td>965</td>
<td>11.5</td>
</tr>
</tbody>
</table>

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 Tucurui 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 Tucurui, 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 Tucurui, 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 0.11, and 0.13 mM in Tucurui, 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 Tucurui, Samuel, and Curuá-Una, respectively.
Fig. 2. Vertical profiles of temperature and concentrations of CH₄, CO₂, 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. 3. Seasonal variation in water discharge and degassing at the turbine outflow of (a) Tucuruí, (b) Samuel, and (c) Curuá-Una dams.

Fig. 4. Variation in the surface concentration and emission of CH₄ and CO₂ 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.
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.
Table 3. Total annual greenhouse gas releases downstream from Amazon hydroelectric dams. All fluxes are in Gg yr\(^{-1}\) of C.

<table>
<thead>
<tr>
<th>Downstream dam</th>
<th>CH(_4)</th>
<th>CO(_2)</th>
<th>CH(_4)</th>
<th>CO(_2)</th>
<th>CH(_4)</th>
<th>CO(_2)</th>
<th>CH(_4)</th>
<th>CO(_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tucurui</td>
<td>169</td>
<td>998</td>
<td>1.5</td>
<td>39</td>
<td>0.3</td>
<td>20</td>
<td>39</td>
<td>81</td>
</tr>
<tr>
<td>Samuel</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Curuá-Una</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Balbina(^a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) 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 Tucurui, 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 (Tucurui, 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.
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.

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References


