

CO₂ emissions from a tropical hydroelectric reservoir (Balbina, Brazil)

Alexandre Kemenes,^{1,2} Bruce R. Forsberg,¹ and John M. Melack³

Received 28 June 2010; revised 28 March 2011; accepted 14 April 2011; published 21 July 2011.

[1] Hydroelectric reservoirs can release significant quantities of CO₂, but very few results are available from the tropics. The objective of the present study was to estimate the emission of CO₂ from the Balbina hydroelectric reservoir in the central Brazilian Amazon. Diffusive and ebullitive emissions were estimated at regular intervals, both above and below the dam, using a combination of static chambers and submerged funnels. Gas releases immediately below the dam were calculated as the difference between gas flux at the entrance and the outflow of the hydroelectric turbines. An inundation model derived from a bathymetric map and daily stage readings was used for spatial and temporal interpolation of reservoir emissions. Annual emissions of CO₂, upstream and downstream of Balbina dam for 2005, were estimated as 2450 and 81 Gg C, respectively, for a total annual flux of 2531 Gg C. Upstream emissions were predominantly diffusive with only 0.02 Gg C yr⁻¹ resulting from ebullition. On average, 51% of the downstream emission was released by degassing at the turbine outflow, and the remainder was lost by diffusion from the downstream river. The total annual greenhouse gas emission from Balbina dam, including the CO₂ equivalent of previously estimated CH₄ emissions, was 3 Tg C yr⁻¹, equivalent to approximately 50% of the CO₂ emissions derived from the burning of fossil fuels in the Brazilian metropolis of São Paulo.

Citation: Kemenes, A., B. R. Forsberg, and J. M. Melack (2011), CO₂ emissions from a tropical hydroelectric reservoir (Balbina, Brazil), *J. Geophys. Res.*, 116, G03004, doi:10.1029/2010JG001465.

1. Introduction

[2] Increases in the concentrations of CO₂ and other greenhouse gases (GHGs) in the Earth's atmosphere during the last century have resulted in a rise in average air temperatures and could lead to major environmental and socio-economic impacts if these trends continue [*Intergovernmental Panel on Climate Change*, 2007; *Hansen et al.*, 2006]. The impoundment of rivers for hydroelectric power generation has contributed to these changes by converting terrestrial ecosystems into wetlands and transforming impounded and inflowing terrestrial and aquatic organic matter into biogenic gas emissions. It has been estimated that emissions from reservoir surfaces represent approximately 4% of CO₂ released from all anthropogenic sources, but very few tropical reservoirs were included in this assessment [*Saint Louis et al.*, 2002]. Ebullitive gas release immediately below hydroelectric turbines, due to the rapid depressurization of reservoir waters, and diffusive fluxes further downstream have been shown recently to contribute significantly to GHG emissions from tropical reservoirs [*Abril et al.*, 2005; *Guérin et al.*, 2006; *Kemenes et al.*, 2007]. Few studies have considered all

potential components of gas flux from hydroelectric systems, and information on these fluxes is especially important in tropical regions where many new dams are expected to be built.

[3] Recent syntheses of the role of inland waters in the global carbon cycle have identified significant processing of organic carbon in lakes, wetlands and rivers [*Cole et al.*, 2007; *Tranvik et al.*, 2009; *Aufdenkampe et al.*, 2011]. A portion of the organic carbon fixed by photosynthesis in these systems and imported from uplands in their catchments, is sequestered in aquatic sediments, a portion is exported via rivers and a large fraction is often released to the atmosphere. As these functions of inland waters have become increasingly apparent, the paucity of relevant information from tropical systems is a serious hiatus in light of the high rates of autotrophic and heterotrophic processes expected in these warm regions.

[4] Balbina is one of the largest reservoirs in tropical South America. Due to its low energy yield per unit of flooded area (~0.14 W m⁻²), Balbina generates a large amount of greenhouse gases with a relatively small energy return [*Fearnside*, 1989]. Regionally significant CH₄ emissions have been measured both upstream and downstream from Balbina dam [*Kemenes et al.*, 2007]. Diffusive losses of CO₂ were also reported below the dam by *Guérin et al.* [2006], based on results from one sampling. Here, we present results of a detailed investigation of CO₂ emissions from the Balbina hydroelectric system, which include year-round measurements of CO₂ emission from multiple sam-

¹Instituto Nacional de Pesquisas da Amazonia, Manaus, Brazil.

²Now at Embrapa Meio-Norte, Teresina, Brazil.

³Bren School of Environmental Science and Management, University of California, Santa Barbara, California, USA.

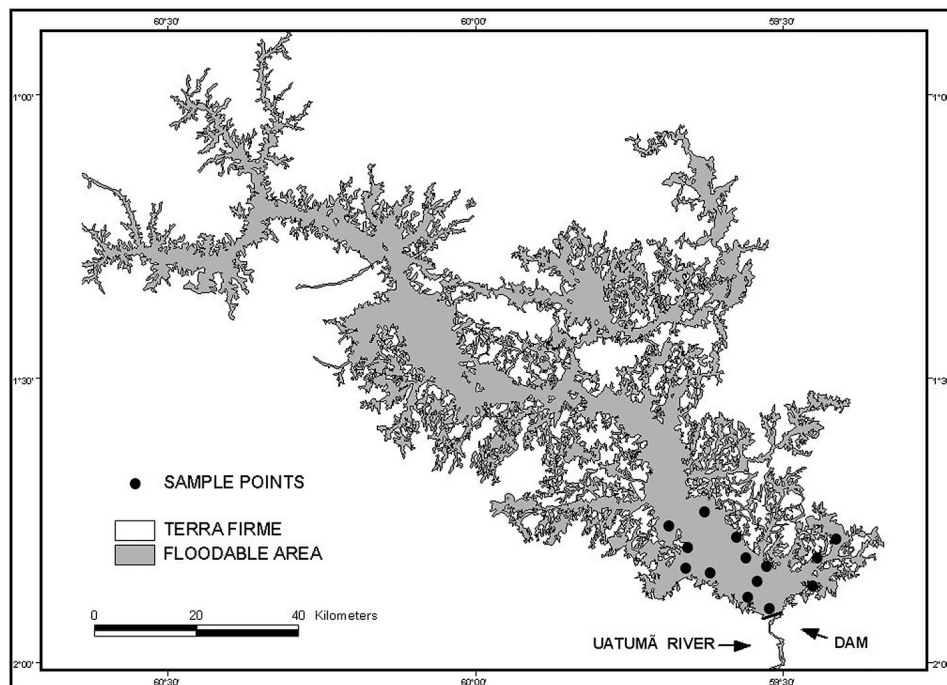


Figure 1. Balbina Reservoir showing location of the dam and reservoir sampling points (solid circles). Extent of flooded area derived from high water L band synthetic aperture radar image acquired by the JERS-1 satellite in 1995.

pling stations, both upstream and downstream from the dam. The total annual emission of CO₂ from the Balbina system is estimated, together with the CO₂ equivalent of emissions of both CO₂ and CH₄. Potential errors in these emission estimates are discussed, as is with the influence of pre-impoundment emissions or sequestration on the emission estimate. Our results contribute to understanding of impacts of reservoirs on GHG emissions and, more generally, to the role of tropical waters in carbon processing.

2. Methods

2.1. Study Area

[5] Balbina reservoir was formed in 1987 by impounding the Uatumã River in the central Amazon basin. The flooded area was dominated by tropical forest growing on the dissected Guianense Complex Formation [RADAM BRASIL, 1978]. This reach of the Uatumã River had a narrow floodplain and no significant alluvial wetlands, and no significant interfluvial wetlands within the drainage [RADAM BRASIL, 1978]. Balbina is the second largest Amazonian reservoir with an average flooded area of 1770 km², an average depth of 10 m and an average water residence time of ~12 months [Kemenes, 2006]. During the study period, water level varied approximately 2 m, which resulted in a surface area change of about 220 km² between high and low water periods. Balbina dam has an average discharge of 570 m³ s⁻¹ and an installed generating capacity of 250 MW [Fearnside, 1989]. The average depth of the turbine intake is about 30 m. Meteorological conditions varied seasonally at the reservoir with the highest rainfall and wind speeds occurring between December and May and the

lowest occurring between June and November (Manaus Energia, unpublished data, 2010, from a meteorological station installed on the dam, equipped with a three-cup anemometer (Campbell Scientific, Inc.) and Ville de Paris rain gauge). Average rainfall and wind speed were 13.8 mm d⁻¹ and 12.3 km h⁻¹ in the rainy period (December–May) and 7.6 mm d⁻¹ and 6.4 km h⁻¹ during the drier season (June–November), respectively.

2.2. Limnological Methods

[6] Limnological characteristics were monitored at 10–14 points on the reservoir (Figure 1) and in the Uatumã River, immediately below the dam, at approximately monthly intervals between September 2004 and February 2006. Measurements on the reservoir were made in conjunction with gas flux estimates at points in open water and inundated forests. Surface and near bottom temperatures, conductivity and dissolved oxygen concentrations were measured with a YSI Model 85 m at all sites. Secchi depth transparency was determined with a 20 cm diameter white disk. Profiles of dissolved oxygen and temperature were obtained just upstream from the turbine intake. Measurements in the Uatumã River were made at the surface near the turbine outflow. pH was measured in situ with an Orion model 250a field pH meter. Water samples for dissolved organic carbon (DOC) were filtered through precombusted (400°C for 12 h) Whatman GFF glass fiber filters and stored in precombusted glass bottles with Teflon cap liners and 10 mg L⁻¹ HgCl₂ as a preservative. DOC concentrations were determined with a Shimadzu 500 TOC analyzer. Daily values of turbine discharge, reservoir stage height, rainfall and wind speed were provided by Manaus Energia.

2.3. Gas Fluxes

[7] To determine CO₂ emissions from the Balbina hydroelectric system, we made regular measurements of surface emissions from the reservoir, gas discharge through the turbines, degassing at the turbine outflow and diffusive emissions in the river channel below the dam.

2.3.1. Reservoir Emissions

[8] Surface emissions from Balbina reservoir were estimated at approximately monthly intervals at 10–14 points between September 2004 and February 2006 (Figure 1). Emissions were measured with static chambers and inverted funnels. The static chambers measured both diffusive and ebullitive fluxes, and the results derived from these measurements are referred to as total emissions. The funnels measured only ebullitive fluxes. The static chamber consisted of a floating cylinder covered with reflective thermal insulation and equipped with an internal fan to improve circulation and maintain ambient temperature. It was allowed to drift freely during deployment. The chamber had 0.23 m² of open area in contact with the water surface and a small diameter connecting tube for withdrawing gas samples. The lower 3 cm of the vertical chamber wall was continually submerged during deployment. During each flux measurement, four gas samples were collected from the chamber at 5 min intervals with 60 ml polyethylene syringes and stored in 20 ml glass serum vials with high density butyl rubber stoppers until analysis [Devol *et al.*, 1990]. All measurements were made in duplicate. The inverted funnels, used to estimate ebullition, had 30 cm diameter mouths and a fitting at the narrow end for collecting gas samples. Funnels were incubated underwater at all sample sites for 24 h. Gas samples collected from the funnels were stored in 20 ml glass serum vials until analysis. Near-surface and near-bottom water samples were collected at each sampling site for determining dissolved gas concentrations. Samples were collected near the bottom with a Ruttner sampler and subsampled at the surface with a 60 ml syringe. Near-surface samples were collected directly with a syringe. Dissolved gas concentrations were determined with the headspace method by equilibrating equal volumes of water and air in the sampling syringe [Johnson *et al.*, 1990]. The equilibrated air samples were transferred to serum vials and stored until analysis. CO₂ concentrations were determined using a dual column gas chromatograph (Shimadzu, model GC-14A) and methodology described by Hamilton *et al.* [1995]. Standards of 335 mg L⁻¹ (SD = 105) and 995 mg L⁻¹ (SD = 104) were used to calibrate the analyses. The detection limit was 100 mg L⁻¹. Chamber emissions for each deployment were estimated from the regression of CO₂ concentration against time. All regressions had $r^2 > 0.90$, indicating that emissions were predominantly diffusive.

[9] Aquatic habitats in the central Amazon basin, including Balbina reservoir, were classified by Hess *et al.* [2003] using 100 m resolution JERS-1 L band synthetic aperture radar mosaics acquired during high and low water periods. A modification of the procedure developed by Hess *et al.* [2003] was used by Kemenes [2006] to distinguish open water and dead forests with varying extent of inundation in Balbina reservoir. Four inundated habitat classes were defined: open water (OW), nearly submerged forest (NSF), moderately inundated forest (MIF), and slightly inundated forest (SIF).

A bathymetric map and inundation model were derived from a geo-referenced bathymetric survey conducted with a Lowrance Inc. LMS - 320 recording sonar. Approximately 3000 km of sonar transects were surveyed covering all parts of the lake basin which were accessible by small boat at high water. Depth measurements were collected at 30 m intervals along these transects, yielding about 100,000 georeferenced data points. All depth values were normalized to peak water level (50 m stage height). The perimeter of the lake at peak stage height was delineated from a wetland mask developed by Hess *et al.* [2003] for the central Amazon basin. The data were interpolated spatially (Spatial Analyst, ESRI, Inc.) to obtain a digital bathymetric map for the lake. The digital bathymetric map was used to develop a nonlinear regression model between reservoir stage height and surface area which was utilized to calculate seasonal variations in reservoir surface area. The influences of depth, temperature, dissolved oxygen, transparency, wind velocity, rainfall, water level change and habitat type on gas fluxes were investigated using an ANCOVA [Sneath and Sokal, 1973].

2.3.2. Degassing at the Turbine Outflow

[10] Degassing immediately below the turbine outflow was estimated as the difference between the gas fluxes at the inflow and immediately below the outflow of the turbines. The gas fluxes at the turbine intake and outflow were calculated as the product of water discharge and gas concentrations measured at the turbine intake and just below the outflow, respectively. Water samples near the turbine inflow were collected at a depth of ~30 m immediately upstream of the dam using a Ruttner sampler that was subsampled at the surface with a 60 ml syringe. Samples were also collected at 1 m intervals above this point to describe the vertical profile of CO₂ concentrations. Water samples at the turbine outflow were collected at a depth of ~0.5 m within 50 m of the dam with a 60 ml syringe. Gas concentrations in these samples were determined by the headspace method described above. The influences of turbine discharge, rainfall and wind velocity on gas flux upstream and downstream of the dam and on turbine emissions were evaluated in separate stepwise multiple linear regression analyses. Only significant variables ($p < 0.05$) were included in the final regression equations used to estimate daily flux rates. Due to the rapid drop in hydrostatic pressure at the turbine outflow and the large rapid drop in CO₂ concentrations (~52%) observed at this point, turbine emissions were assumed to be predominantly ebullitive.

2.3.3. Sampler Comparison

[11] We developed a new sampler, called the Kemenes sampler, designed to avoid degassing losses during the collection of deepwater samples. The sampler consists of a weighted housing which secures a 60 ml polyethylene syringe in a vertical position. Before lowering, a solenoid valve at the mouth of the syringe is closed and a vacuum is applied to the syringe by pulling the syringe piston and securing it in an extended position. At the sample depth the solenoid valve is opened to collect the sample. The sampler and syringe are maintained in a vertical position during retrieval to ensure that any gas bubbles released during the process are retained in the syringe. At the surface, the syringe is treated as indicated in the headspace method described above, ensuring that both the equilibrated gas and any released bubbles are included in the final gas sample.

[12] To quantify the degassing error, we made 11 parallel collections of hypolimnetic waters near the turbine inflows of Balbina, Tucuruí and Samuel reservoirs, using both the Ruttner and Kemenes samplers. The samples were collected between September 2004 and February 2006, following the methodology described above. For depths greater than 20 m, which included most of the depth range expected to contribute to turbine flow in these three systems, the CO₂ and CH₄ concentrations in water samples collected with the Kemenes sampler averaged 34% and 116% higher than those collected with the Ruttner sampler, respectively. The greater difference encountered for CH₄ reflects the lower solubility of this gas and greater tendency to form bubbles when hydrostatic pressure is reduced.

2.3.4. Downstream Diffusive Emissions

[13] After the large ebullitive loss at the turbine outflow, no further evidence of ebullitive emissions was encountered downstream from the dam; hence, surface fluxes estimated with static chambers in the river channel below this point were assumed to represent diffusive emissions. Annual average gas concentrations and diffusive emissions fell gradually from 2450 to 1610 mg C m⁻³ and 417 mg C m⁻² h⁻¹ to 215 mg C m⁻² h⁻¹, respectively, until approximately 30 km below the dam after which they dropped only about 50 mg C m⁻³ and 30 mg C m⁻² h⁻¹, respectively, for the next 40 km. The drop in concentrations during the first 30 km was assumed to represent the degassing of excess CO₂ derived from the dam while the stable value encountered below this point represented the balance between in stream respiration and diffusive emissions. Eight downstream measurement campaigns were done between November 2004 and November 2005. Measurements were made at logarithmically increasing intervals downstream from the dam to represent the large initial decline in values observed immediately below the dam. Diffusive emissions were measured with a drifting static chamber. Surface water samples for dissolved gases were collected with a 60 ml syringe and processed using the headspace method described above. The daily emission for each subreach (area between sampling points) was estimated from the product of the subreach area and the average areal emission rate along the subreach. The values for all subreaches were then summed to estimate daily diffusive emission for the entire reach between the dam and 30 km downstream (see discussion below). The average areal emission was estimated by dividing the total diffusive emission by the total surface area of the study reach. No significant relationships were found between daily emission and environmental variables which could be used for temporal interpolation. Hence, the total annual diffusive emission for the 30 km reach was calculated from the average of the 8 daily estimates times 365. The residual gas flux at 30 km was estimated as the product of water discharge and the dissolved CO₂ concentration measured at that distance.

3. Results

3.1. Limnological Characteristics

[14] Average near-surface water temperature in the reservoir varied from 28°C during the rainy season to 30°C during the drier season. The reservoir was thermally strati-

fied most of the year with an oxycline located around 8 m and a hypoxic hypolimnion (Figure 2). Near-surface dissolved oxygen concentrations ranged from 4 to 7 mg l⁻¹ while near-bottom concentrations varied between 0.5 and 4 mg l⁻¹. Secchi disk transparency in the reservoir varied from 1 to 3 m. Average turbine discharge at the dam ranged from 694 m³ s⁻¹ during the rainy season to 433 m³ s⁻¹ during the drier season. Conductivity in the Uatumã River downstream from the dam varied from 6 to 10 μS cm⁻¹, pH ranged from 6.0 to 7.4, dissolved organic carbon concentrations varied from 2.7 to 7.1 mg l⁻¹ and dissolved oxygen ranged from 4.5 to 7 mg l⁻¹.

3.2. CO₂ Distributions in the Reservoir

[15] The observed ranges of gas concentrations and emission in Balbina reservoir are summarized in Table 1. All variables had normal distributions (Kolmogorov-Smirnov test, $p < 0.05$) and means are arithmetic averages. Concentrations of dissolved CO₂ ranged from 42 to 180 μM at the surface and from 52 to 375 μM near the bottom with average values of 99 and 161 μM, respectively. During the rainy season, the reservoir was weakly stratified with multiple thermoclines above 20 m, and CO₂ concentrations were relatively low and constant in this region (Figure 2). Below 20 m, thermal stratification was stronger and CO₂ concentrations increased with depth. During the drier season, the water column was strongly stratified, and CO₂ concentrations in hypolimnetic waters were higher than those encountered in the rainy season.

3.3. CO₂ Fluxes From Reservoir

[16] Total emission rates of CO₂ (chamber measurements) from the reservoir surface varied from 343 to 8529 mg C m⁻² d⁻¹ with an average value of 3776 mg C m⁻² d⁻¹ and were due almost entirely to diffusive fluxes (Table 1). Ebullitive emissions accounted, on average, for less than 0.02% of the total flux and were not considered separately in the annual flux estimates. Inundated habitats varied seasonally with MIF (37%) predominating at low water, followed by SIF (36%), NSF (24%) and OW (3%), and NSF (50%) predominating at high water, followed by MIF (32%), OW (9%) and SIF (9%). However, variations in habitat type and other environmental parameters had no significant effects on ebullitive emission rates (ANCOVA; $F_{14,56} = 0.5$, $p = 0.50$). An ANCOVA of these same variables against total emission rate was significant ($F_{14,56} = 3.2$, $p < 0.05$), but only due to surface and bottom dissolved oxygen which both had a strong negative effect on flux.

3.4. Integrated Reservoir Emissions

[17] Since oxygen values were measured only occasionally, the statistical relationship between dissolved oxygen and emission could not be used to interpolate total emissions in time. An inundation model and average monthly emission rates were therefore used for this purpose. A quadratic regression model ($F = -0.088 S^4 + 17.8 S^3 - 1321 S^2 + 4296 S - 517590$), relating total flooded area (F) to daily reservoir stage height (S), was derived from the bathymetric data normalized to stage height (Figure 3). Daily emission from the entire reservoir surface (Mg C d⁻¹) was estimated by multiplying the total flooded area, estimated daily with

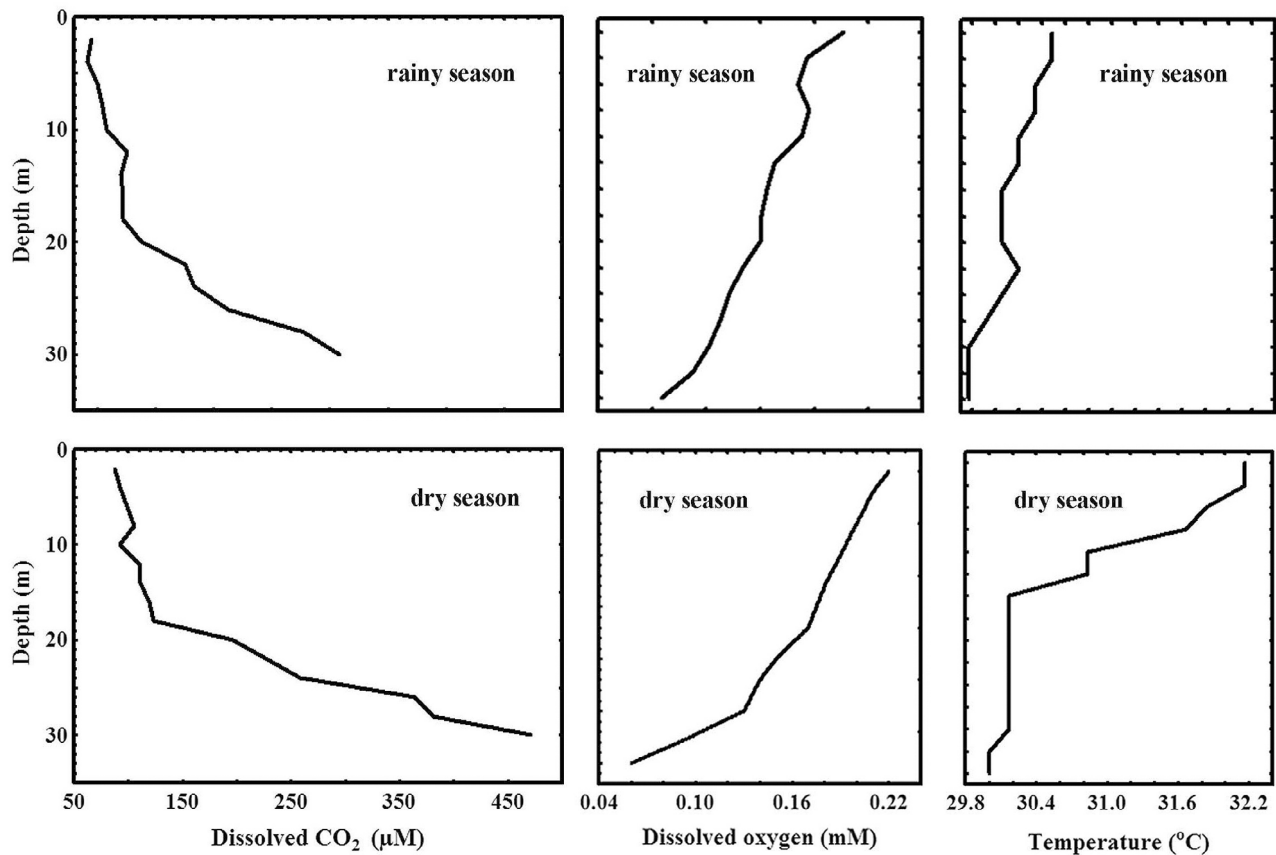


Figure 2. Average vertical profiles of CH₄ and CO₂ concentrations, temperature and dissolved oxygen for rainy and drier seasons at Balbina Reservoir, immediately upstream of the turbines.

this model, by the average monthly areal emission rate (Table 2). During most of year, daily reservoir emissions were positively correlated with flooded area. The few exceptions included unexpected peaks in CO₂ emissions in July, November and December. The total annual emission from the reservoir surface was estimated by integrating daily emissions throughout the year, and during 2005 was estimated to be 2450 Gg C yr⁻¹.

3.5. Degassing of CO₂ at the Turbine Outflow

[18] The average concentrations of CO₂, measured above and below the turbines, were 378 (SD 153) and 215 (SD 66) µM, respectively. The daily discharge of CO₂ at the turbine inflow ($v\text{CO}_2^{\text{inflow}}$) and outflow ($v\text{CO}_2^{\text{outflow}}$) were estimated by multiplying the upstream and downstream concentrations by the daily discharge of water through the turbines. Degassing at the turbine outflow was estimated by the difference between $v\text{CO}_2^{\text{inflow}}$ and $v\text{CO}_2^{\text{outflow}}$. The average rate of degassing determined from the measured fluxes was 100 Mg C d⁻¹. The degassing rate varied during the year with the lowest values occurring during the rainy period (December–May) and the highest levels occurring at the end of the drier season (June–November) (Figure 4a).

[19] To improve the estimate of the annual degassing, we explored correlations with environmental parameters for which we had daily values and found that the best relationships for estimating daily CO₂ discharge at the turbine inflow ($r^2 = 0.48$, $n = 13$, $p < 0.05$) and outflow

($r^2 = 0.42$, $n = 13$, $p < 0.05$) were multiple regressions against daily wind speed and rainfall:

$$v\text{CO}_2^{\text{inflow}} = 397.8 - 11.9 (\text{wind}) - 14.8 (\text{rain}) \quad (1)$$

$$v\text{CO}_2^{\text{outflow}} = 215.6 - 7.6 (\text{wind}) - 10.7 (\text{rain}) \quad (2)$$

These equations were used together with daily wind and rainfall data (Manaus Energia) to estimate the daily gas discharges at the turbine inflow and outflow and the resulting daily ebullitive emissions during 2005. Total annual CO₂ discharge at the turbine inflow was estimated as 78 Gg C yr⁻¹ while degassing at the turbine outflow was estimated to be 41 Gg C yr⁻¹, 53% of the total flux through the turbines.

Table 1. Range of CO₂ Concentrations and Emissions Measured at Balbina Reservoir Between September 2004 and February 2006^a

	Maximum	Minimum
Superficial concentration	180	42
Near-bottom concentration	608	128
Total emission (chamber)	8500	343
Diffusive emission	8500	343
Ebullitive emission	1.3	0

^aHere $n = 72$. Emissions are expressed as mg C m⁻² d⁻¹, and concentrations are expressed as µM.

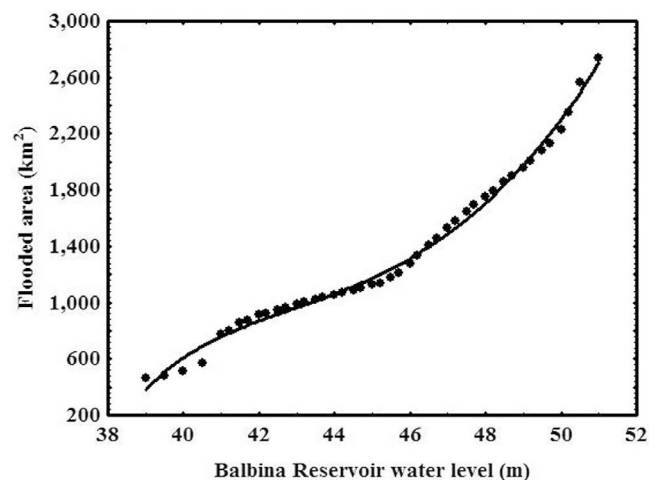


Figure 3. Relationship between lake water level and total flooded area in Balbina Reservoir ($p < 0.05$, $r^2 = 0.88$, $n = 44$).

3.6. CO₂ Fluxes in the Uatumã River

[20] The average surface concentration and real emission rate of CO₂, measured along the 30 km study reach below the dam, were 161 μM and 4790 $\text{mg C m}^{-2} \text{d}^{-1}$, respectively. Both of these values were higher than the average values encountered in the reservoir upstream of the dam. Gas concentrations and fluxes declined slowly below the dam reaching relatively constant values at the end of the 30 km reach (Figure 5). The daily diffusive emission, integrated along the 30 km study reach (Figure 4b), had little seasonal variation. No significant relationships were found between these daily fluxes and measured environmental parameters (ANCOVA, $p < 0.05$). The total annual diffusive emission for the 30 km reach was, therefore, calculated from the average of the 8 daily estimates multiplied by 365 days. The resulting annual flux was 40 Gg C yr^{-1} . The residual discharge of dissolved CO₂ at 30 km was calculated from the mean of 8 measured values, resulting in an annual flux of 41 Gg C yr^{-1} for 2005. The difference between the residual discharge of dissolved CO₂ at the turbine outflow and the sum of the residual discharge at 30 km and the diffusive loss above this location provided an estimate of

Table 2. Average CO₂ Emissions and Flooded Areas at Balbina Reservoir in 2005

Month	Average Emission ($\text{mg C m}^{-2} \text{d}^{-1}$)	Average Flooded Area (km^2)
Jan	3570 ^a	1350
Feb	2160	1400
Mar	2710 ^a	1600
Apr	3260	1870
May	3440	2230
Jun	3770 ^a	2320
Jul	4100	2320
Aug	3870	2220
Sep	2810	2070
Oct	3890 ^a	1980
Nov	4980	1720
Dec	3570 ^a	1620

^aEmissions estimated from mean of adjacent monthly values.

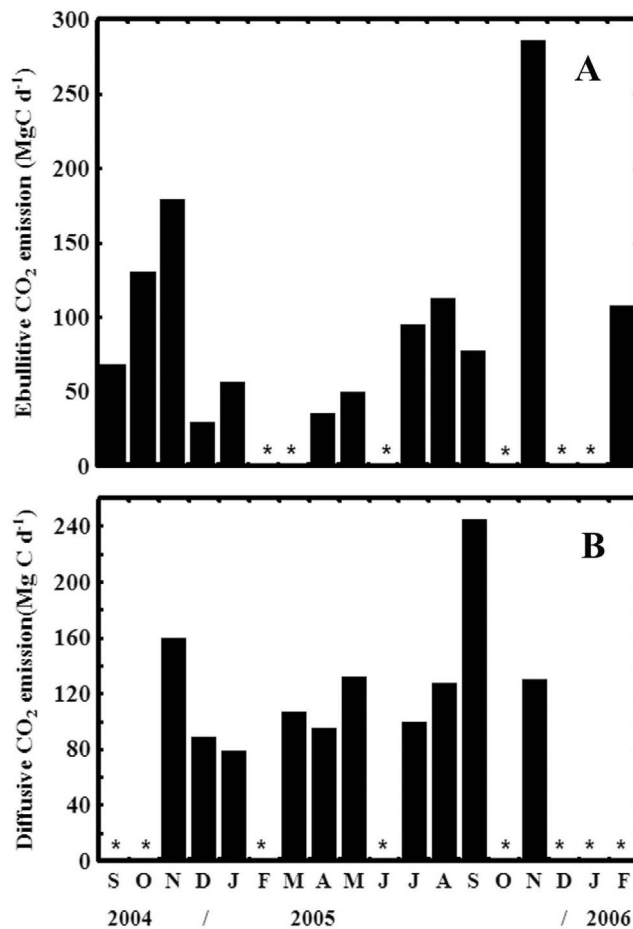


Figure 4. Seasonal variation of (a) initial degassing and (b) diffusive emissions of CO₂ downstream of Balbina dam. Data collected between September 2004 and February 2006. Months without data are indicated with an asterisk.

CO₂ inputs to the river along the 30 km reach. The total residual discharge of dissolved CO₂ at the turbine outflow in 2005 was estimated to be 37 Gg C yr^{-1} , and the input of CO₂ along the study reach was estimated at 44 Gg C yr^{-1} .

3.7. Total CO₂ Fluxes for the Balbina Hydroelectric System

[21] The total annual CO₂ emission for the Balbina hydroelectric system, including emissions from the reservoir, the turbine outflow and the river channel to 30 km below the dam for 2005 was 2531 Gg C yr^{-1} (Table 3). Only 3% of the total flux occurred downstream of the dam. The remaining 97% was released from the reservoir surface. Degassing at the turbine outflow accounted for 51% of the downstream release and the remainder was due to diffusion from the river surface.

4. Discussion

4.1. CO₂ Fluxes From the Reservoir

[22] The average daily CO₂ emission rate from Balbina reservoir was close to the values reported for Tucuruí and Samuel reservoirs [Lima *et al.*, 2002] but considerably higher than those cited for Curuá-Una [Duchemin *et al.*,

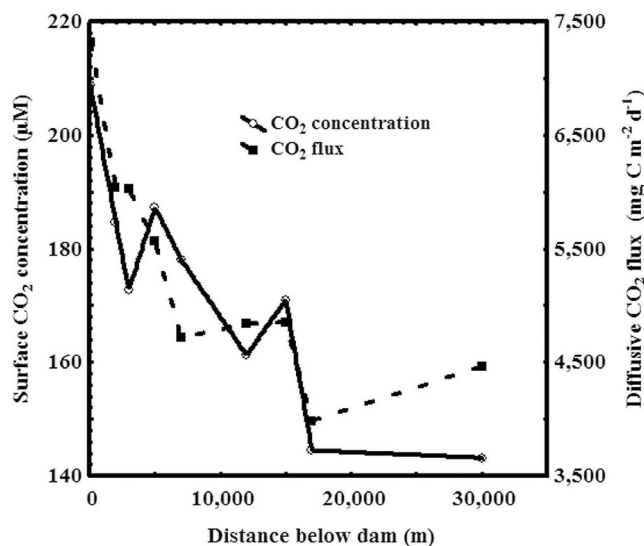


Figure 5. Mean annual variation in surface concentration and diffusive emission of CO₂ downstream of Balbina dam. Data collected between November 2004 and May 2005.

2000] and Petit Saut [Abril *et al.*, 2005] (Table 4). Balbina's value was also significantly higher than the average value of 960 mg C m⁻² d⁻¹ cited by Saint Louis *et al.* [2002] for CO₂ in tropical reservoirs. In an analysis of temperate reservoirs, these authors found a negative log linear relationship between average emission rates and reservoir age. A similar relationship was not encountered for the tropical South American reservoirs listed in Table 4. Lima [2005] attributed the difference in CO₂ emissions rates between Tucuruí and Samuel to the difference in the average depth of the water column that determined the proportion of the CH₄ generated in the sediments that is oxidized to CO₂ as it diffused to the surface. Another source of variability among reservoirs may have resulted from differences in the methods used to measure flux. Guérin *et al.* [2007] found good agreement between gas fluxes estimated with static chambers and eddy covariance measurements when the chamber estimates were made as described here, from a free-drifting boat with a chamber whose lower edge extended well below the water surface. However, Raymond and Cole [2001] argued that the artificial turbulence created by a free drifting

chamber, especially under windy conditions, could significantly affect the measured flux. We did not measure wind speed at the sample sites during measurements. However, average daily wind speeds in the sampling region measured at the dam on the sampling dates were relatively low (0.7–3.7 m s⁻¹) and significant wind driven turbulence was not apparent. The effect of turbulence on the flux measurement would be evident in the piston velocity coefficient, *k*, which is influenced by wind speed, surface temperature and buoyancy [MacIntyre *et al.*, 1995, 2010]. The piston velocity normalized to a water temperature of 20°C, *k*₆₀₀, is generally used to investigate the effects of wind speed and buoyancy on *k* and to compare among studies. The *k*₆₀₀ values, derived following MacIntyre *et al.* [1995], from the CO₂ flux measurements in Balbina Reservoir, varied from 1.1 to 24.7 cm h⁻¹, with an average value of 11.8 cm h⁻¹, while those derived from flux measurements downstream from the dam varied from 0.6 to 21.6 cm h⁻¹, with an average value of 10.5 cm h⁻¹. Four values above 25 cm h⁻¹ were considered high and were omitted from these calculations, although similar values have been reported by Vachon *et al.* [2010]. The *k*₆₀₀ values obtained in Balbina Reservoir were significantly higher than those reported by Guérin *et al.* [2007] for tropical Petit Saut Reservoir (means of 2.34 and 2.93 cm h⁻¹ for wet and dry periods, respectively) which were derived from both static chamber and eddy covariance measurements. However, the results were similar to those obtained with static chambers by Vachon *et al.* [2010] in north temperate lakes (mean = 15.8 cm h⁻¹, range = 8.5–26.5 cm h⁻¹) and reservoirs (mean = 18.8 cm h⁻¹, range = 3.7–31.7 cm h⁻¹). Our *k*₆₀₀ values were also similar to those derived from eddy covariance flux measurements in a north temperate lake [MacIntyre *et al.*, 2010] and based on new regression equations for Lago Curuai in the central Amazon (mean *k*₆₀₀ = 12 cm/h, S. MacIntyre, personal communication, 2010), where the influence of diel variations in thermal stratification, buoyancy flux and wind speed on surface turbulence were all taken into account. Some of the highest *k*₆₀₀ values in these studies were associated with high wind speeds, which were uncommon in our study. However, others are associated with surface cooling and diel mixing which are common in tropical reservoirs. MacIntyre *et al.* [2010] encountered *k*₆₀₀ values exceeding 20 cm h⁻¹ during surface cooling events, even during low wind conditions. The *k*₆₀₀ values obtained here are therefore within the range of values reported in the literature and consistent

Table 3. CO₂ Fluxes for the Balbina Dam System in 2005^a

	Value
<i>Fluxes From Reservoir</i>	
Total emission from reservoir surface	2450
<i>Fluxes Below the Dam</i>	
Degassing at the turbine outflow	41
Residual discharge at the turbine outflow	37
Diffusive emission from river channel for first 30 km reach below dam	40
Residual discharge at 30 km	41
Net gain over 30 km	44
Total emission below dam for 30 km	81
Total emission from Balbina system	2531

^aAll fluxes are in Gg C yr⁻¹.

Table 4. Average Emission Rates for CO₂ and Ages at Time of Study Cited for South American Tropical Reservoirs in Rain Forests

Reservoir	Average Emission (mg C m ⁻² d ⁻¹)	Surface Area km ²	Age (years)
Balbina	3800	1770	22
Tucuruí ^a	3700	2430	25
Samuel ^a	2900	550	21
Curuaí-Una ^b	790	80	32
Petit-Saut ^c	1300	365	15

^aTucuruí and Samuel [Lima *et al.*, 2002].

^bCuruaí-Una [Duchemin *et al.*, 2000].

^cPetit-Saut [Abril *et al.*, 2005].

with the predictions of the most recent physically based models for k600.

[23] The mean daily emission rate for Balbina reservoir was significantly greater than the average value of 2273 mg C m⁻² d⁻¹ reported by Richey *et al.* [2002] for all wetlands in the central Brazilian Amazon and the value of 1860 mg C m⁻² d⁻¹ reported by Devol *et al.* [1988] for open water environments in the same region. The values spanning a year in Lake Curuaí, a large floodplain lake in the lower Amazon, ranged from about 300 to 2300 mg C m⁻² d⁻¹ (C. Rudorff and J. M. Melack, unpublished data, 2010). In vegetated wetlands of the Pantanal diffusive CO₂ evasion was high, ranging from approximately 2070 to 6950 mg C m⁻² d⁻¹ [Hamilton *et al.*, 1995], and in the interfluvial wetlands of the upper Negro basin, average evasion was 2193 mg C m⁻² d⁻¹ [Belger *et al.*, 2011]. In Balbina, no significant differences in emission were detected among the open water and inundated forest habitats sampled (ANCOVA, $p < 0.05$).

[24] In reservoirs, such as Balbina, dissolved CO₂ is derived, in part, from the decomposition of dead trees and organic matter in terrestrial soils inundated during impoundment [Abril *et al.*, 2005; Matthews *et al.*, 2005; Guérin and Abril, 2007; Guérin *et al.*, 2008]. Nogueira *et al.* [2008] estimated forest biomass in the region of Balbina to range from 37.6 to 38.5 GgC km⁻², including all trees >10 cm and both aboveground and belowground biomass. An average value of 38 GgC km⁻² will be assumed for the present analysis. The more labile components (tree crowns, palms, vines, seedlings, litter/root mat) accounted for 28% of this biomass, while more refractory materials (live and dead trunks) and isolated components (belowground biomass) accounted for 41% and 31%, respectively. The labile biomass component is the most likely source of organic carbon for the reservoir in the years immediately following flooding. However, a significant part of the organic carbon bound to more refractory or isolated components can also be released to the reservoir over the following decades [Campo and Sancholuz, 1998]. Cerri *et al.* [2007] estimated organic carbon stocks to vary from 4 to 8 GgC km⁻² in the upper 20 cm of soils surrounding Balbina Reservoir, or an average of 6 GgC km⁻². This is the component of soil carbon most likely to change following land conversion and, therefore, the most probable source of soil organic carbon to the reservoir in the initial years following flooding. An additional 7 GgC km⁻² is estimated to occur to a depth of 1 m [Morães *et al.*, 1995], which may be available over longer time periods. If we consider only the more labile biomass and soil components and extrapolate to the maximum inundated area of the reservoir (~2500 km²), the total organic carbon stock available before inundation would have been 41 TgC, somewhat less than the 47 TgC needed to sustain the carbon emissions observed here (2.6 TgC, including CO₂ and CH₄, see below), if they are extrapolated back to 1987. However, if 40% of the more refractory and isolated biomass and soil components are added, the total carbon stock, 72 TgC, is more than sufficient to sustain the observed emissions, even if the rates immediately following impoundment were moderately higher. Phytoplankton, periphytic algae and herbaceous macrophytes, growing in aquatic environments and terrestrial plants growing in drawdown zones that become inundated as water levels rise also contribute organic carbon to the reservoir as do organic matter inputs

from upstream catchments. Depending on the extent of water level fluctuations and the fertility of the exposed soils, plant growth and decay in drawdown areas can also be a major source of organic carbon [Chen *et al.*, 2009]. The average annual draw down area in Balbina Reservoir between 1995 and 2005, estimated with the inundation model developed here, was 855 km². While plant growth during the terrestrial phase of draw down was not measured in these areas, it could represent a significant source of organic carbon. Dry wetlands, exposed along the central floodplains of the Amazon River at low water, are often colonized by highly productive macrophytes which can contribute significant quantities of organic carbon to these systems [Engle *et al.*, 2008; Melack and Engle, 2009]. Exports of dissolved organic carbon and CO₂ from upland catchments in the Amazon have also been shown to be large [Johnson *et al.*, 2006, 2008] and the 16,300 km² of upland drainage, upstream from the reservoir, contributed significantly to the organic carbon balance and emissions in the system. The CO₂ released from the decay phytoplankton and periphytic algae and their consumers was less important since it is balanced by carbon assimilated during algal photosynthesis [Forsberg, 1985]. Surface CO₂ concentrations in Balbina Reservoir were ~10 times larger than atmospheric saturation, indicating the predominance of heterotrophic metabolism and allochthonous carbon sources in this system.

[25] Spatially integrated CO₂ emissions from Balbina reservoir were generally positively correlated to flooded area. The few exceptions may reflect specific environmental conditions. The high CO₂ emissions observed during the late falling water period (November and December) may reflect an increase in bacterial respiration as the water column became progressively shallower and warmer. The existence of significantly higher surface temperatures and CO₂ concentrations during this period (t test, $p < 0.05$), supports this argument.

[26] We sampled 10–14 sites selected to represent the range of habitats in the reservoir, many more than sampled in other Amazon reservoirs, but these sites were located in the lower third and may not include the full range of spatial variability. However, the magnitude of this uncertainty could not be evaluated.

4.2. Degassing of CO₂ at the Turbine Outflow

[27] Degassing at the turbine outflow accounted for 51% of the total annual emission below Balbina dam, significantly higher than the proportional loss attributed to degassing (18%) below the Petit Saut Dam [Abril *et al.*, 2005], the only other tropical hydroelectric system where this loss has been measured. The higher degassing loss in Balbina is probably due to a difference in design between the two dams. At the Petit Saut Dam, a submerged 20 m high wall was built 150 m upstream of the turbine intake to promote vertical mixing and increase the oxygen level in turbine waters. This increased mixing would also have lowered the CO₂ concentrations in the intake waters and reduced degassing at the turbine outflow. At Balbina, hypolimnetic reservoir waters flows directly into the turbine intake. In addition, the turbine intake in Balbina dam (~30 m) is about twice as deep as that in the Petit Saut dam (~16 m), so hydrostatic pressure is considerably higher in Balbina.

Table 5. Estimates of the Annual Emissions of CH₄ and CO₂ From Above and Below Balbina Dam During 2005, Using Different Assumptions for the Calculation of Gas Concentrations at the Turbine Inflow^a

Emission Component	Assumptions Regarding Upstream Concentration							
	CH ₄ at Intake	CH ₄ at Intake With Degassing	CH ₄ at Hypolimn.	CH ₄ at Hypolimn. With Degassing	CO ₂ at Intake	CO ₂ at Intake With Degassing	CO ₂ at Hypolimn.	CO ₂ at Hypolimn. With Degassing
Ebullition at turbine outflow	73	34	12	6	55	41	34	25
Downstream diffusive flux	5	5	5	5	40	40	40	40
Emission from reservoir	34	34	34	34	2450	2450	2450	2450
Total emission	112	73	51	45	2545	2531	2524	2515

^aAll values are in Gg C yr⁻¹. Assumptions regarding upstream concentration: at intake = sample collected at depth of turbine intake, without degassing loss (Kemenes sampler); at intake with degassing = sample collected at depth of turbine intake, with degassing loss (Ruttner sampler, this study); at hypolimn = concentration integrated through hypolimnion, without degassing loss (Kemenes sampler); at hypolimn with degassing = concentration integrated through hypolimnion, with degassing loss (Ruttner sampler).

4.3. CO₂ Fluxes From the Uatumã River

[28] The residual discharge of dissolved CO₂, not released by degassing at the turbine outflow, was transported downstream in the Uatumã River, and gradually released to the atmosphere by diffusive evasion. Dissolved CO₂ would also be added to the river by the oxidation of organic matter and CH₄ derived from the reservoir, tributaries and floodplain environments or directly as CO₂ discharged from inflowing streams and groundwater. These additional inputs of CO₂ would contribute to the observed diffusive flux. *Kemenes et al.* [2007] estimated the oxidation of CH₄ in the river produced 65% of the emitted CO₂.

[29] The average daily diffusive emission rate for CO₂ in the Uatumã in the first 30 km down stream from the dam (4790 mg C m⁻² d⁻¹) was less than half the value reported by *Abril et al.* [2005] for the first 40 km of the Sinnamary River down stream of Petit Saut dam (11,400 mg C m⁻² d⁻¹). The difference appears to be due to high in situ rates of respiration in the Sinnamary River system. Only 21–25% of total diffusive emissions in the Sinnamary River could be attributed to the discharge of CO₂ from the reservoir after initial degassing below the dam. The remaining emissions were apparently derived from the in situ metabolism of organic matter by riverine bacteria. The contribution of the residual discharge of CO₂ from Balbina (after initial degassing) to the diffusive emissions and final discharge of CO₂ in the Uatumã River (at 30 km) was considerably higher (46%), indicating a smaller relative input from in situ metabolism or lateral sources. Part of the organic matter metabolized in both rivers is presumably derived from the reservoir. Moreover, an additional part is supplied by tributaries and associated wetlands located along the downstream reaches. While the Uatumã River down stream from the dam has a narrow floodplain and few tributaries, the downstream reach of the Sinnamary River includes a large productive estuary which could potentially contribute significant amounts of organic matter to the river.

4.4. Potential Errors

[30] Two potential sources of error in the estimation of downstream degassing in this and our previous study [*Kemenes et al.*, 2007] may have affected our total emission estimates. Degassing estimates were based on the difference between gas concentrations measured at the turbine inflow and outflow. The inflow concentrations were based on measurements made at the depth of the turbine intake which,

on average, was located at ~30 m. While the mouth of the turbine was located at this depth, the duct on the dam that led to the turbines extended from 14 to 30 m depth. Hence, it is possible that the water entering the turbine was drawn from a range of depths. As gas concentrations tended to increase with depth, our method would have resulted in an overestimate of the CO₂ concentrations at the turbine inflow and degassing below the dam. While a detailed study of the velocity field in front of the dam would be needed to evaluate the differential contribution of each depth stratum to turbine inflow, it is unlikely that waters from the stratified metalimnion contributed significantly to this flux. To obtain a lower limit for inflow concentrations, it could be assumed that all hypolimnetic strata below the oxycline were drawn into the duct in equal proportions and that the gas concentration at the turbine inflow represented the numeric average of the concentrations measured at these depths. When emissions were recalculated on this basis, annual degassing fluxes for CH₄ and CO₂ were reduced by 82% and 39%, while total system carbon emissions were reduced by 38% and 0.3%, respectively (Table 5).

[31] Another potential source of error in the downstream degassing estimates may have occurred during the sampling of water near the turbine inflow for dissolved CO₂ and CH₄ analyses. These samples, collected with a Ruttner bottle at a depth of ~30 m, were under elevated hydrostatic pressure and generally supersaturated in both CO₂ and CH₄ in relation to atmospheric equilibrium. As they were brought to the surface and hydrostatic pressure was reduced, a portion of the dissolved gas may have been released as bubbles and not included in the subsamples collected at the surface for dissolved gas analyses. If this loss was significant, it would result in an underestimate of CO₂ and CH₄ concentrations at the turbine inflow and degassing emissions at the turbine outflow. To evaluate the potential magnitude of this error, we compared values obtained with the Ruttner bottle with those expected if we had used the Kemenes sampler, described above. When emissions were recalculated to compensate for the degassing error, annual degassing fluxes for CH₄ and CO₂ were increased by 116% and 34%, while total system emissions were increased by 53% and 0.6%, respectively (Table 5).

[32] The potential errors described above would have opposing effects on the flux estimates. When emissions were recalculated assuming that both effects occur to the degree indicated, annual degassing fluxes for CH₄ and CO₂

Table 6. Annual Emissions of Greenhouse Gases From the Balbina Hydroelectric System^a

Flux Parameter	CH ₄	CO ₂	Total
Upstream of dam	34	2450	
Downstream of dam	39	81	
Total in C	73	2531	
Total in CO ₂ – C	610 (19%) ^b	2531 (81%)	3141

^aAll fluxes are in Gg C yr⁻¹.

^bConverted to CO₂ equivalent carbon using a global warming factor of 23 (kgCO₂/kgCH₄), calculated over a 100 year time horizon.

were reduced by 65% and 17% while total system emissions were reduced by 30% and by 0.3%, respectively (Table 5). Since the degassing error was measured directly, it is likely to reflect the actual error. In contrast, the depth integration correction resulted in a minimum value for the upstream CO₂ concentration so it probably overestimated the true error. Hence, the values indicated in Table 5 represent the lower range of emissions expected for this reservoir. Further studies of the velocity field upstream of the turbine inflow and of degassing errors occurring during deep water sampling will be required to produce more precise emission estimates in this and other hydroelectric systems.

4.5. GHG Emissions for the Balbina Hydroelectric System

[33] Methane emissions from Balbina dam, estimated in an earlier publication [Kemenes *et al.*, 2007], can be added to the CO₂ emissions reported here to estimate the total carbon-based greenhouse gas emissions from this system. Annual CH₄ and CO₂ emissions for the Balbina hydroelectric system, including all upstream and downstream fluxes were 73 and 2531 Gg C yr⁻¹, respectively (Table 6). The downstream fluxes for CH₄ and CO₂ represented ~54 and 3% of the total system fluxes, respectively. A similar percentage for CH₄ (57%) was estimated for a 10 year period in the Petit Saut system and demonstrates the importance of considering downstream fluxes in reservoir emission estimates.

[34] Methane contributes more than CO₂ to global warming on a molar basis due to its high thermal potential, and emissions are often normalized to CO₂ equivalents using a 100 year global warming factor of 23 kgCO₂/kgCH₄ [Ramaswamy, 2001]. Applying this factor to the total CH₄ emission calculated here and adding the resulting flux to the estimated CO₂ emission, yields a total CO₂ equivalent emission of 3 Tg C yr⁻¹, with the relative contribution of CH₄ and CO₂ being 19 and 81%, respectively. The total emission from this one reservoir has the same atmospheric warming potential as 54% of the fossil fuel consumption of the Brazilian metropolis of São Paulo [La Rovere, 1996]. It also represents the equivalent of 2.5% of all CH₄ and 0.5% all CO₂ released from wetlands and river channels in the lowland Amazon basin [Melack *et al.*, 2004; Richey *et al.*, 2002]. Assuming that Balbina's turbines operate at about 50% of their nominal power rating, this results in an atmospheric emission factor of 2.9 tons of CO₂ equivalent carbon per MWh of generated energy, several times higher than that of a coal-fired thermoelectric power plant (0.3 tons C/MWh) [Bosi, 2001]. While Balbina is considered by many to be a worst case in terms of emissions, an

analysis of other South American tropical reservoirs in rain forests [Kemenes *et al.*, 2008] indicated that, when all emission components are considered, most reservoirs generated more emissions per MW of energy than a coal-fired power plant. However, a study of eight hydroelectric reservoirs located in tropical savannas of central Brazil had emissions of only 0.01 to 0.55 tons of CO₂ equivalent carbon per MWh of generated energy (J. P. Ometo, personal communication, 2010).

4.6. Net Emissions

[35] To evaluate the net contribution of Balbina dam to global warming it is necessary to consider the carbon balance of the ecosystem which existed in the region currently occupied by the reservoir before impoundment. If that system was a net source of greenhouse gases, its net emission would have to be subtracted from that estimated here. However, if the system was a net sink for these gases, the preinundation sequestration rate would have to be added to our emission estimate. The reach of Uatumã River which originally flowed through the reservoir area and its associated narrow floodplain were presumably net sources of both CO₂ and CH₄ as has been demonstrated for most rivers and floodplains in the Brazilian Amazon [Richey *et al.*, 2002; Melack *et al.*, 2004]. However, these features occupied only a small fraction of the reservoir area and presumably had a small effect on the regional carbon balance. Most of the region was occupied by upland, tropical broadleaf forest, an ecosystem which has been shown to be a net sink for both CO₂ and CH₄ in several studies [Stuedler *et al.*, 1996; Verchot *et al.*, 2000; Malhi and Phillips, 2004]. Assuming that carbon dynamics in the upland forest dominated the mass balance of CO₂ and CH₄, it is probable that the region currently occupied by the reservoir was originally a net sink for these gases and that the estimates presented here underestimate the contribution of the Balbina reservoir system to atmospheric warming.

[36] **Acknowledgments.** We thank NASA's LBA-ECO program for funding, WWF and CNPq for fellowship support, IBAMA for permission to sample the reservoir and river, and Manaus Energia for logistic support and data.

References

- Abril, G., F. Guérin, S. Richard, R. Delmas, C. Galy Lacaux, P. Gosse, A. Tremblay, L. Varfalvy, M. A. Santos, and B. Matvienko (2005), Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana), *Global Biogeochem. Cycles*, 19, GB4007, doi:10.1029/2005GB002457.
- Aufdenkampe, A. K., E. Mayorga, P. A. Raymond, J. M. Melack, S. C. Doney, and S. R. Alin (2011), Rivers key to coupling biogeochemical cycles between land, oceans and atmosphere, *Front. Ecol. Environ.*, in press.
- Belger, L., B. Forsberg, and J. M. Melack (2011), Factors influencing carbon dioxide and methane emissions from interfluvial wetlands of the upper Negro River basin, Brazil, *Biogeochemistry*, in press.
- Bosi, M. (2001), An initial view on methodologies for emission baselines: Electricity generation case study, 65 pp., Int. Energy Agency, Org. for Econ. Coop. and Dev., Paris.
- Campo, J., and L. Sancholuz (1998), Biogeochemical impacts of submerging forests through large dams in the Rio Negro, Uruguay, *J. Environ. Manage.*, 54, 59–66.
- Cerri, C. E. P., et al. (2007), Predicted soil organic carbon stocks and changes in the Brazilian Amazon between 2000 and 2030, *Agric. Ecosyst. Environ.*, 122, doi:10.1016/j.agee.2007.01.008.
- Chen, H., Y. Wu, X. Yuan, Y. Gao, N. Wu, and D. Zhu (2009), Methane emissions from newly created marshes in the drawdown area of the Three

- Gorges Reservoir, *J. Geophys. Res.*, *114*, D18301, doi:10.1029/2009JD012410.
- Cole, J. J., et al. (2007), Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget, *Ecosystems*, doi:10.1007/s10021-006-9013-8.
- Devol, A. H., J. E. Richey, W. A. Clark, and S. L. King (1988), Methane emissions to the troposphere from the Amazon floodplain, *J. Geophys. Res.*, *93*, 1583–1592.
- Devol, A. H., J. E. Richey, B. R. Forsberg, and L. A. Martinelli (1990), Seasonal dynamics in methane emissions from the Amazon River floodplain to the troposphere, *J. Geophys. Res.*, *95*, 16,417–16,426.
- Duchemin, E., M. Lucotte, R. Canuel, A. G. Queiroz, D. C. Almeida, H. C. Pereira, and J. Dezincourt (2000), Comparison of greenhouse gas emissions from an old tropical reservoir with those of 355 other reservoirs worldwide, *Verh. Int. Ver. für Limnol.*, *27*, 1391–1395.
- Engle, D. L., J. M. Melack, R. D. Doyle, and T. R. Fisher (2008), High rates of net primary productivity and turnover for floating grasses on the Amazon floodplain: Implications for aquatic respiration and regional CO₂ flux, *Global Change Biol.*, *14*, 369–381.
- Fearnside, P. M. (1989), Brazil's Balbina Dam: Environmental versus the legacy of the pharaohs in Amazonia, *Environ. Manage.*, *13*, 401–423.
- Forsberg, B. R. (1985), The fate of plankton primary production, *Limnol. Oceanogr.*, *30*, 807–819.
- Guérin, F., and G. Abril (2007), Significance of pelagic aerobic methane oxidation in the methane and carbon budgets of a tropical reservoir, *J. Geophys. Res.*, *112*, G03006, doi:10.1029/2006JG000393.
- Guérin, F., G. Abril, S. Richard, B. Burban, C. Reynouard, P. Seyler, and R. Delmas (2006), Methane and carbon dioxide emissions from tropical reservoirs: Significance of downstream rivers, *Geophys. Res. Lett.*, *33*, L21407, doi:10.1029/2006GL027929.
- Guérin, F., G. Abril, D. Serça, C. Delon, S. Richard, R. Delmas, A. Tremblay, and L. Varfalvy (2007), Gas transfer velocities of CO₂ and CH₄ in a tropical reservoir and its river downstream, *J. Mar. Syst.*, *66*, 161–172.
- Guérin, F., G. Abril, A. De Junet, and M. P. Bonnet (2008), Anaerobic decomposition of tropical soils and plant material: Implication for the CO₂ and CH₄ budget of the Petit Saut Reservoir, *Appl. Geochem.*, *23*, 2272–2283.
- Hamilton, S. K., S. J. Sippel, and J. M. Melack (1995), Oxygen depletion, carbon dioxide and methane production in waters of Pantanal wetland of Brazil, *Biogeochemistry*, *30*, 115–141.
- Hansen, J., M. Sato, R. Ruedy, K. Lo, D. W. Lea, and M. Medina-Elizade (2006), Global temperature change, *Proc. Natl. Acad. Sci. U. S. A.*, *103*, 14,288–14,293.
- Hess, L. L., J. M. Melack, E. M. L. M. Novo, C. C. F. Barbosa, and M. Gastil (2003), Dual-season mapping of wetland inundation and vegetation for the central Amazon basin, *Remote Sens. Environ.*, *87*, 404–428.
- Intergovernmental Panel on Climate Change (2007), Fourth assessment report, Paris.
- Johnson, K. M., J. E. Hughes, P. L. Donaghay, and J. M. Sieburth (1990), Bottle-calibration static head space method for determination of methane dissolved in seawater, *Anal. Chem.*, *62*, 2408–2412.
- Johnson, M. S., J. Lehmann, E. C. Selva, M. Abdo, S. J. Riha, and E. G. Couto (2006), Organic carbon fluxes within and exports from headwater catchments in the southern Amazon, *Hydrol. Process.*, *20*, 2599–2614.
- Johnson, M. S., J. Lehmann, S. J. Riha, A. V. Krusche, J. E. Richey, J. P. H. B. Ometto, and E. G. Couto (2008), CO₂ efflux from Amazonian headwater stream represents a significant fate for deep soil respiration, *Geophys. Res. Lett.*, *35*, L17401, doi:10.1029/2008GL034619.
- Kemenes, A. (2006), Emissão de metano e gás carbônico pela Hidrelétrica de Balbina, Ph.D. thesis, 98 pp., Inst. Nac. de Pesquisa da Amazônia, Manaus, Amazonas, Brazil.
- Kemenes, A., B. R. Forsberg, and J. M. Melack (2007), Methane release below a tropical hydroelectric dam, *Geophys. Res. Lett.*, *34*, L12809, doi:10.1029/2007GL029479.
- Kemenes, A., B. R. Forsberg, and J. M. Melack (2008), Hidrelétricas e o aquecimento global, *Ciência Hoje*, *41*, 20–25.
- La Rovere, E. L. (1996), The prevention of global climate changes and sustainable energy development in Brazil, in *Greenhouse Gas Emissions Under a Developing Country's Point of View*, edited by L. P. Rosa and M. A. Santos, pp. 215–225, Coord. do Programa de Pos-Grad. de Eng., Univ. Fed. do Rio de Janeiro, Rio de Janeiro, Brazil.
- Lima, I. B. T. (2005), Biogeochemical distinction of methane releases from two Amazon hydro-reservoirs, *Chemosphere*, *59*, 1697–1702.
- Lima, I. B. T., R. L. Victoria, E. M. L. M. Novo, B. J. Freigl, M. V. R. Ballester, and J. P. Ometto (2002), Methane, carbon dioxide and nitrous oxide emissions from two Amazonian reservoirs during high water table, *Verh. Int. Ver. Limnol.*, *28*, 438–442.
- MacIntyre, S., R. Wanninkhof, and J. Chanton (1995), Trace gas exchange across the air-water interface in freshwater and coastal marine environments, in *Biogenic Trace Gases: Measuring Emissions From Soil and Water*, edited by P. Matson and R. Harriss, pp. 52–97, Blackwell, New York.
- MacIntyre, S., A. Jonsson, M. Jansson, J. Aberg, D. E. Turney, and S. D. Miller (2010), Buoyance flux, turbulence, and the gas transfer coefficient in a stratified lake, *Geophys. Res. Lett.*, *37*, L24604, doi:10.1029/2010GL044164.
- Malhi, Y., and O. Phillips (2004), Tropical forests and global atmospheric change: A synthesis, *Philos. Trans. R. Soc., Ser. B*, *359*, doi:10.1098/rstb.2003.1449.
- Matthews, C. J. D., E. M. Joyce, V. L. St. Louis, S. L. Schiff, J. J. Venkiteswaran, B. D. Hall, R. A. Bodaly, and K. G. Beaty (2005), Carbon dioxide and methane production in small reservoirs flooding upland boreal forest, *Ecosystems*, *8*, 267–285.
- Melack, J. M., and D. Engle (2009), An organic carbon budget for an Amazon floodplain lake, *Verh. Int. Ver. Limnol.*, *30*, 1179–1182.
- Melack, J. M., L. L. Hess, M. Gastil, B. R. Forsberg, S. K. Hamilton, I. B. T. Lima, and E. M. L. M. Novo (2004), Regionalization of methane emission in the Amazon Basin with microwave remote sensing, *Global Change Biol.*, *10*, 530–544.
- Morães, J. L., C. C. Cerri, J. M. Melillo, D. Kicklighter, C. Neill, D. L. Skole, and P. A. Steudler (1995), Soil carbon stocks of the Brazilian Amazon basin, *Soil Sci. Soc. Am. J.*, *59*, 244–247.
- Nogueira, E. M., P. M. Fearnside, B. W. Nelson, R. I. Barbosa, and E. W. H. Keizer (2008), Estimates of forest biomass in the Brazilian Amazon: New allometric equations and adjustments to biomass from wood-volume inventories, *For. Ecol. Manage.*, *256*, 1853–1867.
- RADAM BRASIL (1978), Folha SA-20 Manaus: Geologia, geomorfologia, pedologia, vegetação e uso potencial da terra, Minist. de Minas e Energia, Brasília.
- Ramaswamy, V. (2001), Radiative forcing of climate change, in *The Scientific Basis Climate Change 2001*, edited by J. T. Houghton et al., pp. 349–416, Cambridge Univ. Press, Cambridge, U. K.
- Raymond, P. A., and J. J. Cole (2001), Gas exchange in rivers and estuaries: Choosing a gas transfer velocity, *Estuaries*, *24*, 312–317.
- Richey, J. E., J. M. Melack, K. Aufdenkampe, V. M. Ballester, and L. L. Hess (2002), Outgassing from Amazonian rivers and wetlands as a large tropical source at atmospheric CO₂, *Nature*, *416*, 617–620.
- Saint Louis, V. C., C. Kelly, E. Duchemin, J. W. M. Rudd, and D. M. Rosenberg (2002), Reservoir surface as sources of greenhouse gases to the atmosphere: A global estimate, *BioScience*, *20*, 766–775.
- Sneath, P. H. A., and R. R. Sokal (1973), *Numerical Taxonomy*, 234 pp., W. H. Freeman, San Francisco, Calif.
- Steudler, P. A., J. M. Melillo, and B. J. Feigl (1996), Consequence of forest-to-pasture conversion on CH₄ fluxes in the Brazilian Amazon, *J. Geophys. Res.*, *101*, 18,547–18,554.
- Tranvik, L. J., et al. (2009), Lakes and reservoirs as regulators of carbon cycling and climate, *Limnol. Oceanogr.*, *54*, 2298–2314.
- Vachon, D., Y. T. Prairie, and J. J. Cole (2010), The relationship between near-surface turbulence and gas transfer velocity in freshwater systems and its implications for floating chamber measurements of gas exchange, *Limnol. Oceanogr.*, *55*, 1723–1732.
- Verchot, L. V., E. A. Davidson, and J. H. Cattânio (2000), Land use change and biogeochemical controls of methane fluxes in soils in eastern Amazonia, *Ecosystems*, *3*, 41–56.

B. R. Forsberg, Coordenação de Pesquisas em Ecologia, Instituto Nacional de Pesquisas da Amazonia, C.P. 478, Manaus, AM 69011-970, Brazil. (brforsberg@gmail.com)

A. Kemenes, Embrapa Meio-Norte, Av. Duque de Caxias, 5650, C.P. 001, Teresina, PI 64006-001, Brazil.

J. M. Melack, Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106-5131, USA.