

Variability of carbon dioxide flux from tropical (Cerrado) hydroelectric reservoirs

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Abstract Hydroelectric reservoirs generate energy without significant combustion of fossil fuels. However, these systems can, potentially, emit greenhouse gases (GHG's) at a rate which may be significant at the global scale, and, possible, co-equal, per kilowatt-hour, to that from conventional coal or oil-fired systems. Although much of the new construction of hydroelectric reservoirs is in the tropics, most of the data on GHG emissions comes from temperate regions. Further, much of the existing data on reservoir gas emissions comes from single sites, usually near the terminal dams. Large tropical reservoirs often involve the impoundments of river systems with complex morphology which in turn can cause spatial heterogeneity in gas flux. We evaluated spatial and seasonal variability in CO₂ concentrations and gas flux for five large (50–1,400 km²) reservoirs in the Cerrado region of Brazil. Most of data set (87% of all measurements) showed CO₂ supersaturation and net efflux to the atmosphere. There was as much or more variation in pCO₂ over space and among seasons. The large studied reservoirs showed different

zones in terms of CO₂ emission because those fluxes are dependent on flooded biomass, watershed input of organic matter and dam operation regime. Here we demonstrate that the reservoirs in the Brazilian Cerrado have low rates of CO₂ emissions compared to existing global comparisons. Our results suggest that ignoring the spatial variability can lead to more than 25% error in total system gas flux.

Keywords CO₂ emission · Hydroelectric reservoirs · Spatial heterogeneity · GHG · Tropical freshwaters

Introduction

The exchange of metabolic gases across the air–water interface is an important and integrative property of aquatic ecosystems and one vector of connection to their terrestrial watersheds. Aquatic systems can also be conduits for terrestrially produced CO₂ from the input of high concentrations of CO₂ in groundwater, as a result of soil respiration (e.g. Kling et al. 1991; Palmer et al. 2001; Jones et al. 2003). A majority of freshwater ecosystems are supersaturated in CO₂, which means that these systems are a net source of CO₂ to the atmosphere (Cole et al. 1994). It is known that different processes are responsible for carbon dioxide dynamics in the water column including: bacterial respiration, photooxidation (Granéli et al. 1996), surface and groundwater inflow of aqueous CO₂ (alkalinity (HCO₃⁻ and CO₃⁻) (Stets et al. 2009); and CO₂ production in sediments (Cole et al. 1994; Duarte and Prairie 2005). However, this excess CO₂ is often assumed to be largely the result of respiration of allochthonous organic matter exceeding phytoplankton primary production (del Giorgio et al. 1997; Sobek et al. 2005). According to Duarte and

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Prairie (2005), the correspondence between aquatic metabolism and CO₂ emissions or uptake need to be explicitly tested and not only assumed, as there are processes that may confound the relationship between aquatic metabolism and CO₂ emissions.

The emission of CO₂ and other greenhouse gases (GHG's) from hydroelectric reservoirs is a topic of scientific debate when considering alternative energy production. In some cases, observations suggest that the total GHG emissions from reservoirs are comparable, per kilowatt hour, to that of traditional coal or oil-fired thermoelectric production (Rudd et al. 1993; Fearnside 2004; Giles 2006). If true, hydroelectric power may not result in lowering GHG emissions. This idea has been contested (Rosa et al. 2004; Dos Santos et al. 2006). The controversy continues in part because of the paucity of studies of GHG emissions from hydroelectric reservoirs, particularly in tropical regions where there are reservoirs especially the largest ones (see Lima 2005; Guerin et al. 2006; Kemenes et al. 2007), and continue to be built (St. Louis et al. 2000).

Large impoundments may show different zones in terms of CO₂ emission because those fluxes are dependent on flooded biomass, watershed input of organic matter and dam operation regime. Estimating gas emissions from larger reservoirs is complicated by the high potential for spatial variability in these fluxes. Most currently available data have not constrained this spatial variability, although the potential causes are observable. Large hydroelectric reservoirs, especially those created by impounding rivers, are morphometrically complex and quite spatially heterogeneous. Different sections of these systems inundated during their construction offer differing parts of the terrestrial landscape with vastly different amount of organic C. Further, along their lengths these reservoirs can receive new terrestrial C from multiple tributaries. Downriver degassing emissions can also be a significant part of gas emissions from tropical reservoirs (Abril et al. 2005, Guerin et al. 2006, 2007; Kemenes et al. 2007).

Heterotrophic and autotrophic activity plays an important role in CO₂ emissions and dynamics in reservoirs. The role of both heterotrophic and autotrophic activity along reservoirs has been reported in studies of subtropical, tropical and temperate areas (Robarts and Wicks 1990; Di Siervi et al. 1995; Richardot et al. 2000; Bukaveckas et al. 2002; Raymond and Cole 2003; Lauster et al. 2006; Jugnia and Dévaux 2008; Jugnia et al. 2006; Finlay et al. 2009). While several studies focusing on gases in both the water column and sediment have been performed (Duchemin et al. 1995; Bergstrom et al. 2004; Guerin et al. 2007), few of these describe or discuss spatial variability in GHG fluxes. Although one would expect reservoirs to be spatially heterogeneous in their CO₂ fluxes to the atmosphere,

most studies on reservoir GHG emissions look at these emissions at a single site, usually close to the terminal dam.

Here, we evaluated spatial and temporal variability in *p*CO₂ saturation for five tropical hydroelectric reservoirs in the Cerrado (Savannah) of Brazil, based on different analytical approaches. Our working hypothesis was that measurements from a single site would lead to erroneous estimates of CO₂ flux from the entire surface area of the reservoirs.

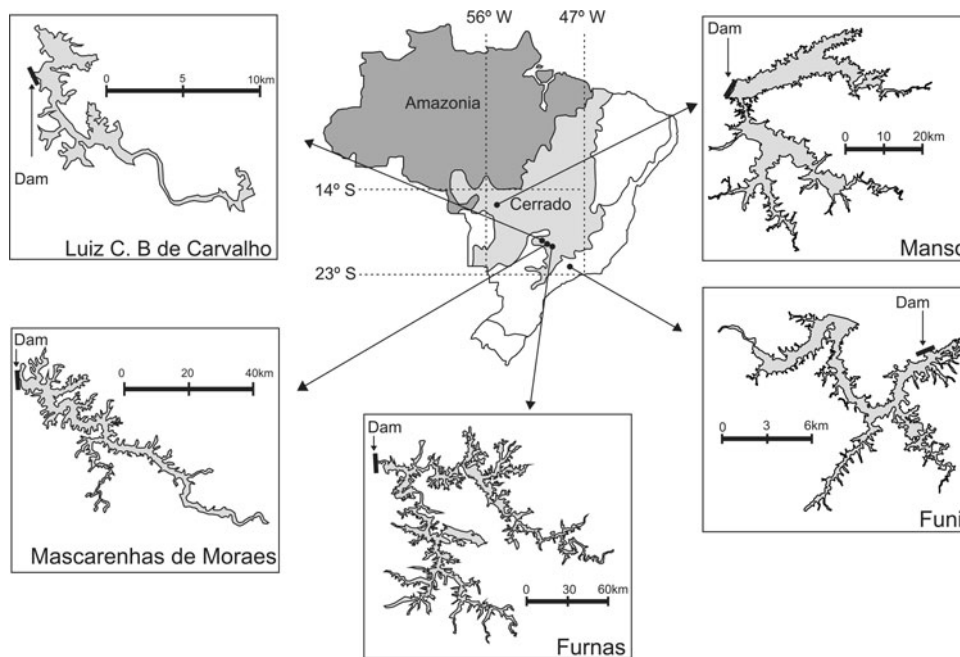
Methods

Hydroelectric reservoirs

Five reservoirs are included in this study: Furnas-FNS, Mascarenhas de Moraes-MSM, Luiz Carlos Barreto de Carvalho-LBC, Manso-MAN and Funil-FUN (Fig. 1). Prior to flooding, the original vegetation type was the Cerrado biome (Savannah), which is situated on poor soils overlying pre-Cambrian rock. The climatic region is humid tropical (*A_w*; Niemer 1989), with a rainy season during summer and a dry period (June–August) in the austral winter. The latter season is not pronounced and average temperature for the coldest month is above 18°C. All five reservoirs are used for the generation of electricity. They are different in age, size and hydrology (Table 1) and they are between the range mesotrophic (MAN) and slightly eutrophic (FNS, MSM).

Sampling and analysis

The partial pressure of CO₂ (*p*CO₂) was measured on several spatial and temporal scales on the whole body of the reservoir. This required different analytical approaches. For the spatially extensive data set, discrete samples to directly measure static *p*CO₂ were taken during cruises that encompassed the entire length of each reservoir. The samples were taken during two seasons for FUN and MAN (rainy, March 2007; dry, August 2007). FNS, MSM and LBC were sampled only during a single dry season (August 2006). For each of the reservoirs, *p*CO₂ samples were taken at approximately every kilometer along the length of the reservoir. For sampling at the river after the dam, only one site was sampled on the river just after the dam for MAN, FUN and LBC. FUR and MSM are connected to each other such that the output of FUR enters a river that then enters MSM. By sampling FUR near its river outlet and MSM near its river inlet, we could estimate the gas loss during the river that connects them. We had data to support this calculation on two seasons on the field campaigns dates (rainy, 21–27 March 2007 and dry, 08–25 July 2007).

Fig. 1 Location of the studied hydroelectric reservoirs**Table 1** Location and general features of the five reservoirs

	Reservoirs				
	FNS	MSM	LBC	MAN	FUN
Coordinates	20°39'S 46°18'W	20°16'S 47°03'W	20°09'S 47°16'W	14°52'S 55°46'W	22°35'S 44°35'W
Year of operation	1963	1957	1969	2000	1969
Generate electricity (Mega Watt)	1,216	476	1,050	210	180
Main river	Grande	Grande	Grande	Manso	Paraíba do Sul
Maximum depth (m)	89	43	55	40	45
Mean depth (m)	15	15	29	19	20
Area (km ²)	1,342	250	45	360	27
Volume (km ³)	20.7	3.8	1.3	6.5	0.5
Watershed area (km ²)	51,773	59,355	60,897	9,365	16,680
Organic carbon-soil (kg C m ⁻²) ^a	4.3	5.3	4.7	5.3	4.7
Hydrological rivers input (m ³ s ⁻¹)	780	969.3	938.9	192.6	204.8
Residence time (years)	1.38	0.14	0.05	2.47	0.09
Outlet position	Epilimnion	Metalimnion	Metalimnion	Epilimnion	Epilimnion
Elevation (m)	755	673	638	388	470
Annual mean air tempertaure (°C)	20.2	21.6	22.5	25.3	18.4
Annual precipitation (mm)	1,126	1,525	1,455	1,241	1,337

Area and volume correspond to the respective year of study; maximum depth is average among seasons at the station nearest to the dam; residence time is daily average during the sampling month. Year of operation is the first year that power was generated

FNS Furnas, *MSM* Mascarenhas de Moraes, *LBC* Luiz Carlos Barreto de Carvalho, *MAN-R* Manso rainy season, *MAN-D* Manso dry season, *FUN-R* Funil rainy season, *FUN-D* Funil dry season

^a Average from the watershed soil

Concomitant with the CO₂ work, samples for other water chemistry measures (alkalinity, temperature and pH) were taken using a polyethylene bottle. The water for pCO₂ measurements was taken at 0.5-m depth between 8:00 and

12:00 a.m. Measurements of pCO₂ was made directly using the headspace equilibrium method (Hesslein et al. 1991; Cole et al. 1994). Fifteen mL atmospheric air was equilibrated with 20 mL reservoir water by vigorous

shaking for 1 min (Cole and Caraco 1998). The headspace gas was transferred to a plastic syringe, and the concentration of CO₂ in the headspace gas was immediately measured using an infrared gas analyzer (IRGA—environmental gas monitor EGM-4; PP Systems). Three complete replicates for each sampling site were taken (e.g., three separate equilibrations). To evaluate the degree of humidity interference on IRGA measurements, we compared ambient (humid) air to air dried by passing it through a drying tube filled with indicating drierite, as suggested by the IRGA Operations Manual (EGM-4; PP Systems). Using 25 measurements, no significant difference was found comparing measurements with and without the drying tube ($t = 2.3$, $P > 0.05$; $n = 25$).

For the time-intensive data set, a 15 day interval, $p\text{CO}_2$ was calculated from continuous, hourly values of pH and temperature and daily measurements of alkalinity (ANC) at a single site near the dam in each reservoir. These sites are instrumented with a “smart buoy” called SIMA (Environmental Integrated Monitoring System) which collects, stores and transmits key hydrogeochemical data for the reservoirs, including water and air temperature and wind speed, and detailed temperature profiles (<http://www.dpi.inpe.br/sima/bancos/index.php>). The SIMA buoy supports thermistor chains with 4 thermistors over a depth of 35 meters with temperature recorded every 60 s. Additional data for pH and surface temperature were obtained by attaching a sonde (YSI model 6920), and exchanging and calibrating it every 15 days according YSI Environmental Operations Manual (<http://www.ysi.com/ysi/support>). We use standard solutions (pH 4, 7, and 10) to calibrate each pH sensor. Alkalinity (ANC) was also measured by titration using 0.01 N sulfuric acid whenever we sampled for IRGA measurements. Besides the daily measurements (time-intensive data set), we measured ANC at every single site spatially distributed across the $p\text{CO}_2$ —IRGA measurements. This generated 462 direct measurements of ANC or an average of 39 (FUN) to 86 (MAN-R) in each reservoir depending of reservoir area. Because the spatial variation in ANC was small ($\text{CV} = 0.76\text{--}1.24$), we assumed that the short-term temporal variation was also small. We calculated $p\text{CO}_2$ from ANC, pH, and temperature according to Stumm and Morgan (1996). Water samples for measurements of total organic carbon (TOC) were analysed using a Carbon Analyzer (Phoenix 8000), where the total dissolved organic carbon was measured as CO₂, following high temperature oxidation with a UV lamp. Before TOC analysis, inorganic carbon was eliminated from the samples by phosphoric acid addition and sparging for 6 min with N₂-free air. At least three measurements of TOC were made for each sample; the coefficient of variation (CV) was considered acceptable when $<2\%$.

For both the spatially and temporally intensive data sets, values of $p\text{CO}_2$ in equilibrium with the atmosphere were calculated according to Cole et al. (1994), using Henry’s law and the equations in Weiss (1974). The exchange of CO₂ with the atmosphere depends of CO₂ concentration in the water (CO₂ aq). The concentration in the water would be in equilibrium with the atmosphere (CO₂ sat) and the physical rate of exchange (k). The equilibrium with the atmosphere was assumed to be 365 μatm (Sobek et al. 2006). In Eq. 1, k is the gas evasion coefficient and is dependent on wind speed according to the following equation, normalized to Schmidt number of 600 (Cole and Caraco 1998). The gas transfer velocity was calculated based on the same wind speed used to calculate fluxes.

$$\text{CO}_2 \text{ Flux} = k\alpha(p\text{CO}_2 \text{ aq} \times kh - p\text{CO}_2 \text{ sat}) \quad (1)$$

$$k_{600} = 2.07 + 0.21 U_{10}^{1.7} \quad (2)$$

In Eq. 2, U_{10} is wind speed at 10-m height and k_{600} is the piston velocity in cm h^{-1} for a gas with a Schmidt number of 600 (Jahne et al. 1987). The daily average wind speed was obtained at SIMA at 3-m height and was calculated to 10-m height during the investigation period and was used in all flux calculations between air and water (Smith 1985). The chemical enhancement factor, α , was calculated from k and pH according to Wanninkhof and Knox (1996).

Spatial data analysis and statistical procedures

In order to evaluate the spatial variability on the $p\text{CO}_2$, a spatial model was applied for each reservoir. Modeling the spatial structures was carried out through variogram analysis. Variograms are the key function in geostatistical analysis used both to describe the spatial correlation among samples of a variable acquired in different locations and to spatially interpolate them using kriging (Bailey and Gatrell 1995). An empirical variogram is used as a first estimate of the (theoretical) variogram. In the study, the empirical variograms were fitted to different mathematical models using Akaike’s information criterion (AIC, Akaike 1974) to evaluate the best fit. The parameters extracted from the best fitted model were used to facilitate interpolation by ordinary kriging. We used the Ordinary Kriging to produce the in situ $p\text{CO}_2$ map. The sampling pattern was highly dense (approximately $1 \times 1 \text{ km}$) which minimizes the uncertainty of the interpolation. Moreover, a cross test was made to evaluate the reliability of the maps. This cross-validation removes each measured point per turn, predicts a value for that location based on the rest of the data, and compares the measured and predicted values. The made interpolation based on this modeling grid was robust enough to validate the maps. This map enables the visualization of spatially distributed $p\text{CO}_2$. The mean standardizing error was low (<0.02) for all reservoirs.

In support of more detailed studies of mixing events in MAN, we needed a bathymetric map. A Triangulated Irregular Network (TIN) was used to the level curves interpolation in order to generate the declivity along the longitudinal axis of MAN reservoir. Every 0.5 km from the entrance of the Manso river on the reservoir until the dam zone, the depth was measured using an echobathymetry (GPSMAP 520s Garmin). For each reservoir, a shoreline development index (SDI) was calculated in accordance with Wetzel and Likens (2000). Data to calculate the SDI (area and perimeter of the reservoir) came from Environmental Department of Furnas Centrais Eléctricas S. A. (<http://www.dsr.inpe.br/projetofurnas/>). It describes the roundness of a lake or the degree of dissectedness of the shore line. Lakes with values near 1 are circular and have little shoreline development.

For statistical procedures, t-tests were used to detect significant differences between $p\text{CO}_2$ measured by sonde and by IRGA. Linear regression was used to test the degree of spatial variability among reservoirs in relation to different parameters and to check the tendency between sonde and IRGA data. Statistical analyses were performed using the software JMP (Version 5.0.1). For all statistical tests, we assumed $P < 0.05$ as a threshold level for acceptance.

Results

Spatial and temporal variability in $p\text{CO}_2$

Among reservoirs, partial pressure of CO₂ measurements varied widely from 291 to 3,079 μatm (from about half to 8 times higher than atmospheric equilibrium value). In the reservoirs where seasonal variation was measured (MAN and FUN), there was an increase in $p\text{CO}_2$ levels during the dry season. The $p\text{CO}_2$ varied from 291 to 3,079 μatm in the rainy season and 708 to 2,837 μatm in the dry season at MAN reservoir and from 295 to 1,155 μatm in the rainy season and 394 to 1,508 μatm in the dry season at FUN reservoir. There was no significant difference between seasons ($t = 1.9$, $P > 0.05$) in either Manso and Funil reservoirs, if we consider the full spatial data. However, we found higher values in the dry season for both systems, if we compare zones with higher values of $p\text{CO}_2$ ($t = 2.2$, $P < 0.05$). We also found the same pattern comparing data from the dam zone ($t = 2.1$, $P < 0.05$). The river post dam $p\text{CO}_2$ were generally higher and varied from 865 (MSM) to 3,079 μatm (MAN-R).

In addition, $p\text{CO}_2$ varied spatially within each reservoir (Fig. 2). In general, the areas close to the riverine inflow

Fig. 2 Partial pressure of CO₂ ($p\text{CO}_2$; μatm) in a spatial scale expressed by a color gradient obtained from an interpolation of measured data using the Ordinary Kriging statistical procedures (see text). The gray gradient represents the scattering from undersaturation (lightest gray) to supersaturation (darkest gray)

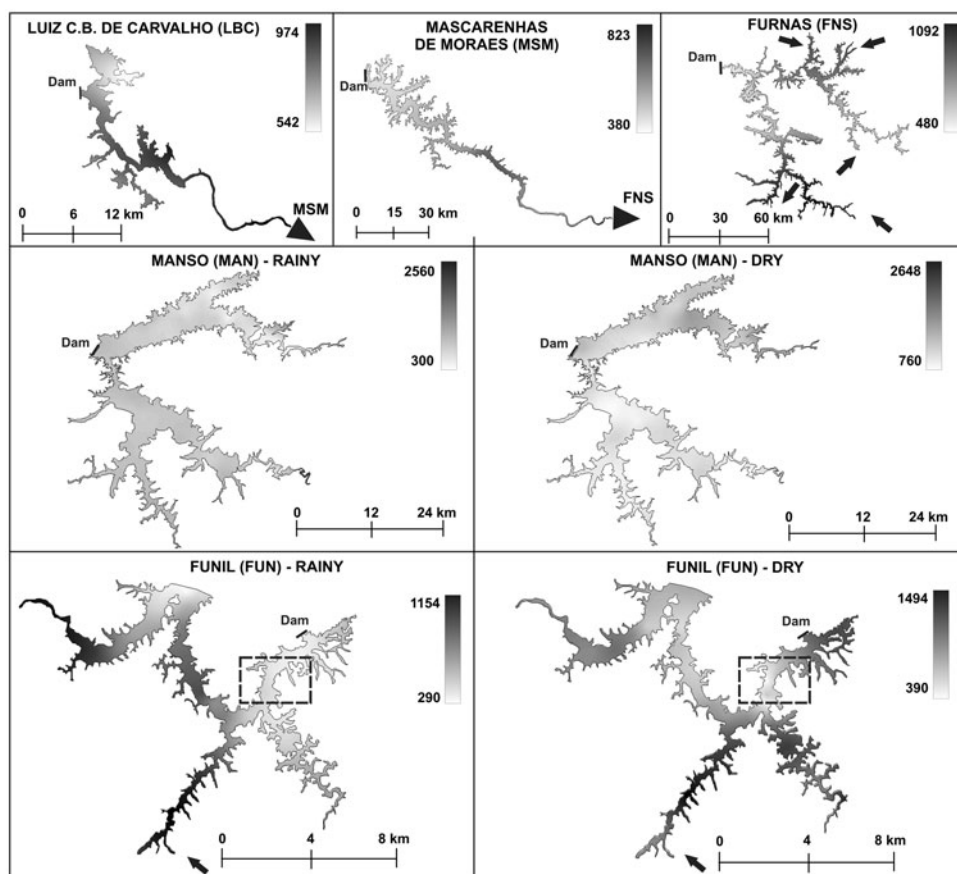


Table 2 Data of coefficient of variation of $p\text{CO}_2$, fluxes of CO_2 (IRGA, $\text{mmol m}^{-2} \text{ day}^{-1}$), fluxes of CO_2 (probes, $\text{mmol m}^{-2} \text{ day}^{-1}$), TOC—tributaries (means, mgC L^{-1}), TOC—reservoir before dam (means, mgC L^{-1}), watershed area:reservoirs area ratio, Shoreline Development Index, wind speed at 10 m (m s^{-1}), k value (cm h^{-1}), total alkalinity ($\mu\text{Eq L}^{-1}$), temperature ($^\circ\text{C}$)

	Reservoirs						
	FNS	MSM	LBC	MAN-R	MAN-D	FUN-R	FUN-D
Coefficient of variation of $p\text{CO}_2$	0.22	0.29	0.13	0.46	0.40	0.37	0.35
Fluxes of CO_2 (IRGA; $\text{mmol m}^{-2} \text{ day}^{-1}$)	9	13	23	8	33	10	11
Fluxes of CO_2 (Probes; $\text{mmol m}^{-2} \text{ day}^{-1}$)	12	38	64	72	105	−130	−136
TOC—tributaries (mean; mgC L^{-1})	3.1	2.2	2.2	2.2	2.9	4.4	3.9
TOC—reservoir before dam (mean; mgC L^{-1})	1.3	1.5	1.5	1.5	2.6	4.0	2.5
Watershed area:reservoir area ratio	39	237	1353	26	26	627	627.0677
Shoreline development index	20	9	8	9	9	13	12.68943
Wind speed at 10 m (m s^{-1})	2.99	3.73	4.87	2.29	4.68	2.33	2.86
K value (cm h^{-1})	3.5–3.6	4.3–4.5	5.5–5.7	3.1	5.2–5.8	3.3–3.8	3.4
Total alkalinity ($\mu\text{Eq L}^{-1}$)	206–282	243–257	243–254	196–402	231–377	344–405	313–394
Temperature ($^\circ\text{C}$)	20.8–21.9	21.9–23.4	22.07–22.6	27–31	23–24.5	26–29	20.5–21

See “Methods”

had higher levels of $p\text{CO}_2$ than the main body of the reservoir. We observed decreasing $p\text{CO}_2$ towards the dam and increasing values downriver of the dam for all the systems. Based on the coefficient of variation (CV) of $p\text{CO}_2$ for each reservoir, there was a wide range in variability. The CV's for spatial data sets varied between 0.13 (LBC reservoir) and 0.46 (MSM-R reservoir). However, there was about equal ranges of variability temporally to the MAN and FUN reservoirs (Table 2).

The $p\text{CO}_2$ spatial variability changed as a result of physical event associated to water vertical mixing movement from the bottom to the surface. The mixing event was identified by examining the temperature profiles and meteorological parameters from the SIMA site (Fig. 4a, b). From the temperature isopleths (Fig. 4b), mixing occurred to a depth of 23 m. The mixing event appeared to follow a series of strong winds (Fig. 4a, b). Peaks of rain and, especially sudden increases in wind speed (Fig. 4a; arrows) show conditions to promote mixing of the water column (Fig. 4b). From end of April to July, seven cold fronts reached Manso Reservoir (arrows in Fig. 4b). Further details about the action of cold front in Manso Reservoir can be found in Lorenzetti et al. (2005). After the event, the zone close to the dam became much more supersaturated than before (Fig. 3a, b). The spatial distribution of $p\text{CO}_2$ in MAN reservoir was negatively correlated with maximum depth in each section of the reservoir (Fig. 3c). Figure 3c shows $p\text{CO}_2$ measurements plotted across a depth gradient in a moment without evidence of any mixing in the whole reservoir water column. Each peak in wind speed was associated with a steep fall of air temperature during the cold front passage. Air temperatures declined

about 6°C during these events and daily average wind reached 6 m s^{-1} . Thus, the deepening of the surface mixing layer due to the stirring from the wind stress will be enhanced by downward convective mixing in dry seasons.

The degree of spatial variability among reservoirs was correlated with several features of the systems and not with others (Fig. 5). Neither the index of shoreline development nor reservoir area explained more than 3% of the variability in the coefficients of variation of $p\text{CO}_2$ (Fig. 5a, b). However, three characteristics (residence time per unit reservoir area; watershed area; and TOC input per unit watershed area, each explained a large fraction (69–78%; and all significant at $P < 0.05$) of this variability (Fig. 5c, d, e). The tributaries showed higher TOC concentration compared to the concentrations found in the reservoir before the dam (Table 2). The values varied from 2.2 to 4.4 mgC L^{-1} in tributaries and from 1.3 to 4.0 mgC L^{-1} in the reservoir before the dam. The watershed area:reservoir area ratio varied from 26 to 1,353 and the shoreline development index from 8 to 20.

Time-intensive temporal data set of $p\text{CO}_2$

The temporal $p\text{CO}_2$ measured by multi-parameter sonde (temperature and pH) and alkalinity showed that there is also wide seasonal variability in the sampled reservoirs. The $p\text{CO}_2$ varied between 344 and 1,177 μatm (Fig. 6). LBC and MAN were prevalent on $p\text{CO}_2$ supersaturation, while FNS and FUN-dry were prevalent on $p\text{CO}_2$ undersaturation. Considering all the temporal data across all

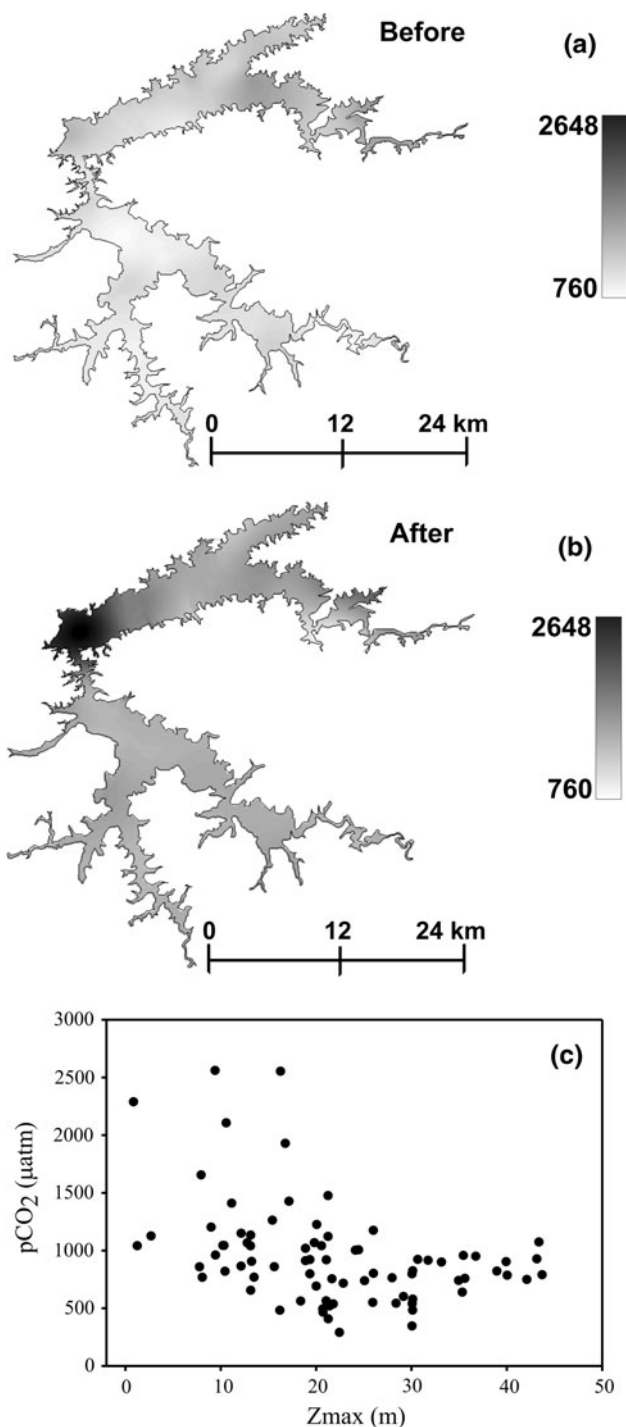


Fig. 3 $p\text{CO}_2$ data (μatm) in Manso reservoirs during the dry season. Spatial distribution of $p\text{CO}_2$ before (a) and after a mixing event (b). The *gray* gradient on both panels represents the magnitude of $p\text{CO}_2$ data using the Ordinary Kriging statistical procedures (see text). $p\text{CO}_2$ measurements plotted across a depth (Z_{max}) gradient in a moment without evidence of any mixing in the whole reservoir water column (c)

5 reservoirs, daily data sets, 84.2% of the daily means were above the atmospheric equilibrium, 13.7% were below atmospheric saturation, and the remaining 2.1% were within 5% of atmospheric equilibrium.

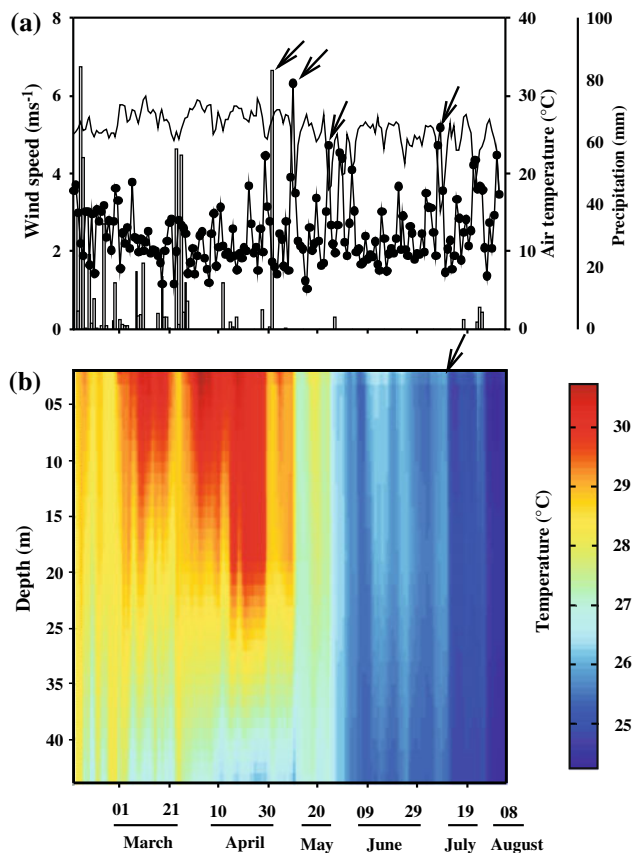


Fig. 4 Climatological data (*upper panel*) showing air temperature ($^{\circ}\text{C}$; *lines*), wind speed (m s^{-1} ; *dotted lines*) and precipitation (mm ; *bars*). The *bottom panel* shows the daily water temperature profiles on the water column. Data were observed between the end of the rainy season (March) and dry season (July) at Manso reservoir

High temporal frequency versus spatial variability

The $p\text{CO}_2$ was estimated using either the sonde at SIMA sites (calculated) and IRGA (direct) present were significantly different (Fig. 7, t test = 1.96, $P < 0.05$). However, the tendency between sonde and IRGA data shows that they are well correlated ($r^2 = 0.73$, $P < 0.05$). In general, the sonde-based data were more variable than IRGA data, and overestimated $p\text{CO}_2$ up to 65% on average compared to the IRGA (Table 2). This is likely caused by small error in the pH probes measurements or calibration which have a strong effect on calculated $p\text{CO}_2$ (Herczeg and Hesslein 1984).

Discussion

Several studies of hydroelectric reservoirs have suggested that these systems may add significant CO_2 and CH_4 to the atmosphere at a global scale (Rudd et al. 1993; St. Louis et al. 2000; Tremblay et al. 2004; Roehm and Tremblay 2006), and have expressed concern about the rapid rate of

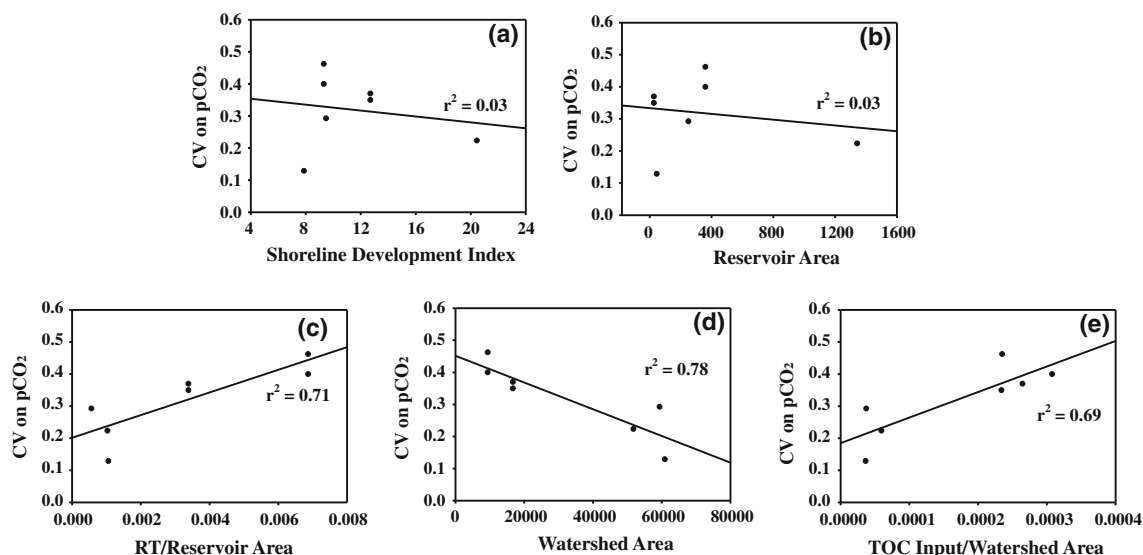


Fig. 5 Regression results describing simple relationships between coefficient of variation (CV) of $p\text{CO}_2$ versus Shoreline Development Index (a); CV on $p\text{CO}_2$ versus reservoir area (b); CV on $p\text{CO}_2$ versus

residence time (RT):reservoir area ratio (c); CV on $p\text{CO}_2$ Watershed area ratio (d); CV on $p\text{CO}_2$ versus TOC in: watershed area ratio (e). *Significance level $P < 0.05$

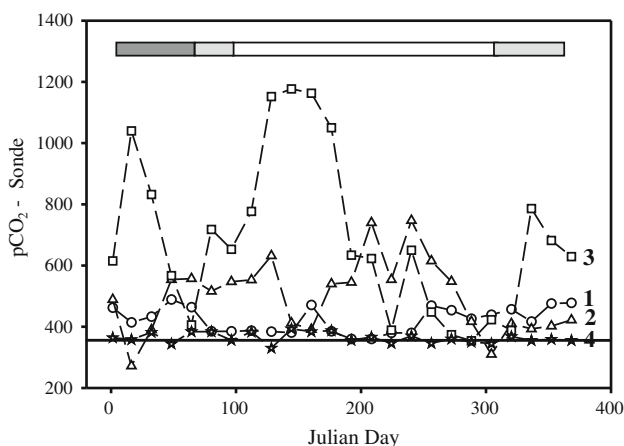


Fig. 6 Temporal series of $p\text{CO}_2$ (μatm) for four reservoirs: Furnas (1; circle); Luiz C. B. de Carvalho (2; triangle), Manso (3; square) and Funil (4; star). The line represents the atmospheric equilibrium (365 μatm). The upper bar indicates the intense rainy (dark gray), discrete rainy (gray) and dry (empty) seasons

construction of new dams, especially in the tropics. Our study shows that reservoirs in the tropical Cerrado region of Brazil are, like other reservoirs, predominately CO_2 supersaturated (Table 2), and in general sources of CO_2 to the atmosphere. These CO_2 fluxes, however, are considerably smaller than those reported for many reservoirs to date. For example, the mean CO_2 fluxes from our study ranged from -2.2 (influx) to an efflux of $108.9 \text{ mmol C m}^{-2} \text{ day}^{-1}$ (mean = 16.50 and median = 13.9 $\text{mmol C m}^{-2} \text{ day}^{-1}$) among reservoirs. The mean flux reported by St. Louis et al. (2000) for global hydroelectric reservoirs was $59.8 \text{ mmol C m}^{-2} \text{ day}^{-1}$. Furthermore, our study shows that

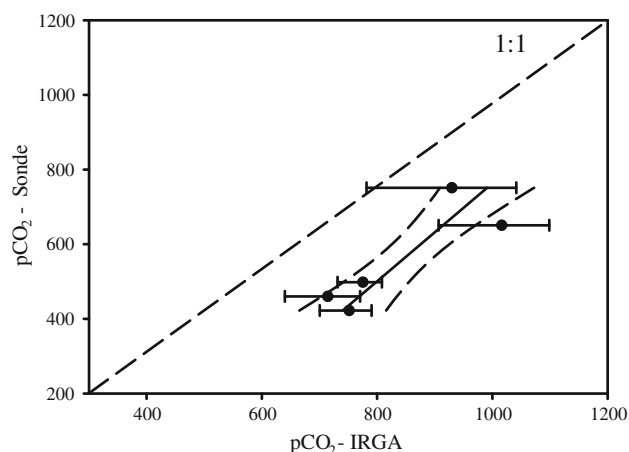


Fig. 7 Relationship between $p\text{CO}_2$ (μatm) estimated by sonde (Y) and by IRGA (X). Each value represents mean and standard deviation for each reservoir sampled in time and space (FNS, MSM, LBC, MAN and FUN). The dashed lines represent the 99% confidence interval. The equation of regression is $\text{Sonde} = 0.798 \times \text{IRGA} + 393.45$ ($r^2 = 0.73$, $P = 0.0285$)

CO_2 saturation varies both seasonally and over space in large tropical reservoirs. Kelly et al. (2001) found higher seasonal variation compared to spatial variation and showed that in natural temperate lakes, a single spot should be adequate to determine if a lake is above or below equilibrium with the atmosphere.

Our study found as much more variation over space than between wet and dry seasons, representing the extremes in temporal variability. Had we used only the data near the dam, as in most reservoir studies, as the sole location for the calculation of $p\text{CO}_2$, we would have underestimated

flux by more than 25%, or as much as 32% in some reservoirs. In our systems, the site closest to the dam tended to have the lowest $p\text{CO}_2$ saturation compared to other sites (Fig. 8). We suggest, therefore, that the reservoir systems may need to be re-examined spatially before we can have confidence in flux estimates.

We observed consistent spatial patterns in $p\text{CO}_2$ in all the studied reservoirs. For example, the higher elevated $p\text{CO}_2$ at some sites in FNS and FUN co-occurred with the locations of significant sewage outfalls (Soares et al. 2008). Further, some reservoirs receive CO₂ rich hypolimnetic waters from upstream reservoirs, such as in cascade reservoirs. The main MSM reservoir is located just after the dam of FNS. The higher $p\text{CO}_2$ near the dam (in the reservoir) of FNS promoting high downriver degassing in MSM. Similarly, LBC is just downriver of the MSM dam and is similarly influenced by the hypolimnetic water from MSM (Fig. 2). Another factor that likely causes spatial variation in $p\text{CO}_2$ is variation in reservoir depth. In the one system for which we have good bathymetric data (MSM), $p\text{CO}_2$ was clearly higher in the shallows and lower in the deep regions (Fig. 3c). It is likely that variation in depth contributes to spatial variability in the other systems as well.

Our original hypothesis, that variability would be related to morphometric complexity was not supported. The variability could be partially understood by a combination of morphological and hydrological parameters. Neither the index of shoreline development, nor reservoir area, nor water residence time were significantly correlated, among reservoirs, to variability in $p\text{CO}_2$. On the other hand, some parameters (watershed area; the ratio of water residence time to reservoir area) were strongly correlated with this variability (Fig. 5). We do not have a mechanistic explanation for these relationships, and it is probably premature

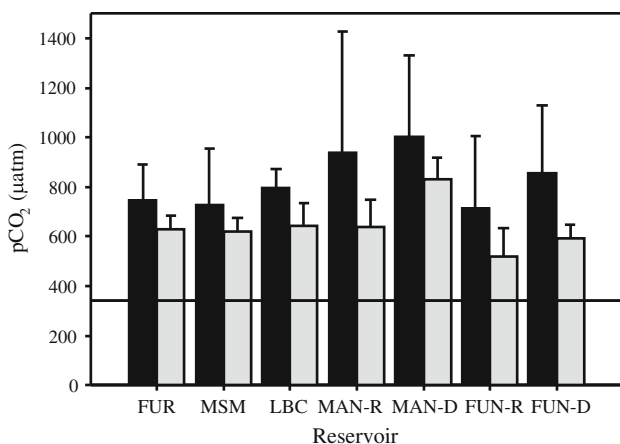


Fig. 8 Comparison, for every hydroelectric reservoir, between $p\text{CO}_2$ data (mean and SD) measured in all sites along the reservoir (black bars) and those measured only near the dam (gray bars)

to propose a conceptual model based only 5 reservoir systems. Nevertheless, the strong positive correlation between spatial variability and RT:RA is striking in that there is no significant correlation to either RT or RA alone. That the reservoirs with the smallest watersheds, independent of other factors, had the greatest spatial variation is also surprising.

The water level in hydroelectric reservoirs is strongly driven by the operation of the dam, since the turbines must generate power by water fluxes. This procedure sucks water from the reservoir, potentially enhancing spatial variability in $p\text{CO}_2$. Moreover, during the intense tropical rainy season, the excess water must be dropped downriver through the spillway. This induced water transportation promotes internal currents that may effect mixing (Galy-Lacaux et al. 1997). Furthermore, the position of the outlet is a potential in-system driver of patterns in $p\text{CO}_2$ distribution. The reservoirs in which the outlet is positioned in the hypolimnetic layer, FUN for example, deep waters highly supersaturated in $p\text{CO}_2$ (unpublished data) is pumped downriver removing some or much of this water before water column mixing takes place. A strong inverse correlation between $p\text{CO}_2$ and Z_{max} (maximum depth) was observed in Manso reservoir (Fig. 3c). Regions shallower than 20 m deep showed a higher variation in $p\text{CO}_2$ values (CV = 0.48) when compared to deeper regions (CV = 0.24). The higher and more variable $p\text{CO}_2$ values in shallow regions may be related to higher inputs of organic matter; more intense hydrodynamic interferences; variability in benthic metabolism, and a lack of stability of the water column. The higher inputs of organic matter to shallow regions are related to the fact that these are usually riverine or marginal zones, which are more closely connected to the terrestrial environment. Shallow regions are more susceptible to the effects of hydrodynamic interferences. Vertical mixing events, especially if caused by intense winds, for instance, may easily disturb the sediments of shallow regions. While we have only one documented mixing event in our data set (Figs. 3, 4), these events and their legacies might cause some of the observed spatial variability. Finally, the lack of stability of shallow water regions is related to a less frequent stratification, and, thus, to a more frequently mixed system.

Meteorological events like storms and thermal winds play a crucial role in the gas fluxes in reservoir (Abril et al. 2005), promoting a multiplicative effect on the instantaneous atmospheric fluxes. The gas concentration increases at the surface by vertical mixing. We documented an example of this physical process in MAN (Fig. 3a, b).

In summary, the spatial variability in CO₂ flux from hydroelectric reservoirs is probably caused by a combination of in-system and external forces. Hydrodynamic events linked to depth and residence time appears to be key

factors modulating $p\text{CO}_2$ spatial patterns. External forces like watershed dimension and input of carbon play combined actions explaining the variability. Our measurements in both spatial and temporal scales show that continuous data at single sites (high temporal frequency data) can provide real estimates in time but may miss zones with high fluxes. For our reservoirs, the continuous time series at the dam sites underestimated CO_2 flux by up to 30% compared to full spatial data. Future reservoirs gas studies should strive to include spatial variation.

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