Spatial variation of sediment mineralization supports differential CO2 emissions from a tropical hydroelectric reservoir

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INTRODUCTION

Significant efforts have been made to understand the carbon fluxes into and out of inland waters. However, discerning the pathways of carbon flow, especially related to aquatic sediments, remains uncertain (Cole et al., 2007). For instance, the relationship between the allochthonous carbon loaded to aquatic ecosystems and the portion either mineralized or buried in sediments has yet to be better quantified (Battin et al., 2009; Sobek et al., 2011). Inland waters (e.g., lakes and reservoirs) receive large amounts of allochthonous organic matter (OM) transported from the surrounding watershed, part of which is sedimented. Once in the sediment, OM can have three major fates: (i) mineralization by aerobic or anaerobic bacteria and release back to water column as CO2 and CH4; (ii) re-suspension and mineralization in the water column; or (iii) burial in the sediment. The relative importance of each of these three processes is system-specific and influences the overall role of a system as net sink or source of carbon as greenhouse gases (GHG) to the atmosphere (Mendonça et al., 2012a). The limited knowledge of the lateral transport of carbon from soils, and its fate in lakes and reservoirs results in incomplete understanding of the terrestrial carbon balance (Tranvik et al., 2009).

Hydroelectric reservoirs are man-made freshwater ecosystems that can substantially alter regional and global carbon balance. During the first years after impounding, the mineralization of flooded vegetation and soils cause significant emissions of GHG to the atmosphere (Mendonça et al., 2012b). Growing demand for energy has motivated the construction of hydroelectric reservoirs worldwide. There are approximately 45,000 large hydroelectric reservoirs in operation in the world (World Commission on Dams [WCD], 2000), with a total surface area of about 350,000 km2 (Bacros et al., 2011). In Brazil, the increasing number of hydroelectric reservoirs in pristine areas (e.g., Amazon and Pantanal) has generated controversy among local people and among the scientific community worldwide (Fearnside, 2006; Sousa Júnior and Reid, 2010). One source of dispute is the effect of river damming on aquatic GHG emissions. In this context, estimating

Substantial amounts of organic matter (OM) from terrestrial ecosystems are buried as sediments in inland waters. It is still unclear to what extent this OM constitutes a sink of carbon, and how much of it is returned to the atmosphere upon mineralization to carbon dioxide (CO2). The construction of reservoirs affects the carbon cycle by increasing OM sedimentation at the regional scale. In this study we determine the OM mineralization in the sediment of three zones (river, transition, and dam) of a tropical hydroelectric reservoir in Brazil as well as identify the composition of the carbon pool available for mineralization. We measured sediment organic carbon mineralization rates and related them to the composition of the OM, bacterial abundance and pCO2 of the surface water of the reservoir. Terrestrial OM was an important substrate for the mineralization. In the river and transition zones most of the OM was allochthonous (66 and 48%, respectively) while the dam zone had the lowest allochthonous contribution (7%). The highest mineralization rates were found in the transition zone (154.80 ± 33.50 mg C m⁻² d⁻¹) and the lowest in the dam (51.60 ± 26.80 mg C m⁻² d⁻¹). Moreover, mineralization rates were significantly related to bacterial abundance (r² = 0.50, p < 0.001) and pCO2 in the surface water of the reservoir (r² = 0.73, p < 0.001). The results indicate that allochthonous OM has different contributions to sediment mineralization in the three zones of the reservoir. Further, the sediment mineralization, mediated by heterotrophic bacteria metabolism, significantly contributes to CO2 supersaturation in the water column, resulting in higher pCO2 in the river and transition zones in comparison with the dam zone, affecting greenhouse gas emission estimations from hydroelectric reservoirs.

Keywords: freshwater sediment, carbon mineralization, stable isotopes, pCO2, heterotrophic bacteria, hydroelectric reservoir, Brazil
inputs and outputs of OM in hydroelectric reservoirs is important in order to better understand the impacts of these systems on the environment and to support regional and global evaluations of the environmental costs and benefits of hydroelectric energy generation.

In tropical freshwater ecosystems, sediment OM is mineralized by aerobic and anaerobic respiration and fermentation resulting in the production of CO2 or CH4. The occurrence of aerobic or anaerobic processes in the sediment is regulated by the availability of electron acceptors (e.g., oxygen, nitrate, manganese, iron, and sulfate; Fenchel et al., 1998). Especially in the case of reservoirs, these processes are also regulated by mixing regimes, thermal structure of the water column and productivity (Kalif, 2002) that vary along a longitudinal gradient, resulting in the establishment of different zones. Those zones are mainly the area close to the river inflow, the transitional area between the river and the dam of the reservoir, and a lacustrine zone directly influenced by the dam of the reservoir (Thorton et al., 1990; De Junet et al., 2009). Additionally, the magnitude of the carbon degradation across reservoir zonation can be related to the amount and quality of organic carbon (OC) available (Conrad et al., 2010, 2011), plankton metabolism (Forbes et al., 2012), oxygen concentrations (Sobek et al., 2009) and the temperature of the water overlaying the sediment (Ciais et al., 2010). Despite the mineralization processes in the sediment are gaining more attention in aquatic ecosystems (Algesten et al., 2005; Bardin et al., 2009), studies considering the mineralization in the sediment of hydroelectric reservoirs are still rare, particularly in tropical areas.

In this study, our goal was to determine the OM mineralization in the sediment of three zones (river, transition, and dam) of a tropical hydroelectric reservoir in Brazil as well as characterize the source of the carbon pool available for mineralization. The results indicate that OM mineralization in the sediment vary along the different zones of the reservoir. It is mostly influenced by the allochthonous carbon pool and significantly contributes to CO2 supersaturation in the water column affecting GHG emissions from the system.

MATERIALS AND METHODS

STUDY AREA DESCRIPTION

This study was conducted in the Manso Reservoir (14°52’S, 55°46’W) in January of 2009. The reservoir is located in southeastern Brazil, in the Cerrado (savannah-type) biome. It is a large (360 km2) and deep (maximum depth 40 m) hydroelectric reservoir Brazil, in the Cerrado (savannah-type) biome. It is a large (360 km2) and deep (maximum depth 40 m) hydroelectric reservoir Brazil, in the Cerrado (savannah-type) biome. It is a large hydroelectric reservoir in Brazil as well as character-ize the source of the carbon pool available for mineralization. The results indicate that OM mineralization in the sediment vary along the different zones of the reservoir. It is mostly influenced by the allochthonous carbon pool and significantly contributes to CO2 supersaturation in the water column affecting GHG emissions from the system.

ANALYTICAL METHODS

Water samples from the reservoirs were analyzed for pH using a pH meter (Micronal B474), DO concentrations with a Clark-type oxygen sensor coupled to a picoumperimeter (Unisense©, model PA 2000) and DIC following sodium persulfate digestion on a Tekmar-Dohrmann TC analyzer (model Phoenix 8000). The pCO2 was measured in the water overlying the cores and in the water surface of the reservoir using an infrared gas analyzer (IRGA- environmental gas monitor IGM-4; PP Systems). Measurements of pCO2 were made directly using the headspace equilibrium method (Heusel et al., 1991; Cole et al., 1994). Fifteen mL of atmospheric air was equilibrated with 20 mL of 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 was immediately measured on the IRGA. Bacterial abundance from the overlying water of the sediment was estimated by direct counting using the
acridine orange method (Hobbie et al., 1977) under an Olympus BX60 fluorescence microscope. Sediment samples of OM were analyzed by loss on ignition and TP by the colorimetric method according to Carmouze (1994). Concentrations of TC and TN in the sediment were analyzed according to Mackeeth et al. (1978) using a PerkinElmer analyzer. Sediment particle sizes were quantified using a Malvern laser diffraction particle size analyzer. For the determination of water content and porosity, subsamples of fresh sediment were weighed in ceramic vessels and their weight loss recorded after heating for 4 days at 60°C (Dalsgaard et al., 2000).

The particulate organic carbon (POC) concentration and the stable isotope ratios of POC and sediment samples were analyzed using a gas isotope ratio mass spectrometer (Delta Plus, Finnigan Mat). One replicate sample and standards were analyzed after every set of 10 samples. Carbon isotopic ratios were expressed using delta notation as the ratio of the heavy to the light isotope ($\delta^{13}C$) over the ratio of the heavy to the light isotope of the international standards $\delta^{13}C$ Pee Dee Belemnite, respectively. Isotope ratios of the OM samples were used to determine the allochthonous contribution to the OM pool (Gu et al., 2011). We estimated the upper and lower limits for the contribution of each carbon source (autochthonous and allochthonous) to mineralization in the different zones of the reservoir by using a two-source isotope mixing model (Fry, 2006): terrestrial material and algae. Macrophytes were excluded from the sources due to the low abundance in the sampled sites.

The end members (OM sources) for the two-source mixing model were determined as follows: during the sampling period there was a bloom of algae in the reservoir. POM samples were acquired by passing subsurface water samples through a glass fiber filter (0.7 μm porosity). Subsurface water samples were also used for phytoplankton analysis. The phytoplankton analysis showed dominance in abundance and composition (90%) of the cyanobacteria Microcystis aeruginosa in the POM samples. The $\delta^{13}C$ of these samples, $-30.10\%o$, was used as the pelagic end member in the mixing model. During the samplings there was no visual confirmation of macrophytes along the reservoir. As the rivers are known to have a predominant contribution of allochthonous material in the surface waters (Kalff, 2002) we used POM samples from the surface water of this zone for isotope analysis. The $\delta^{13}C$ value of these samples ($-19.26\%o$) was used as the allochthonous end member in the mixing model. Differences in OC mineralization, $pCO_2$ in the incubation chambers and the surface waters, and bacterial abundance in the sediment among zones was tested using ANOVA, followed by Tukey’s post hoc test performed in SigmaPlot 11.8.

RESULTS

The suspended POC stable isotope composition varied over depth and between the different zones (river, transition, and dam; Figure 2). In the river, $\delta^{13}C$ values decreased from $-19.26$ (surface) to $-20.32$ (middle), and to $-21.51$‰ (bottom). An opposite pattern was found for $\delta^{13}C$ values in the dam $-30.10$ (surface),
Table 1 | Organic matter (OM), total carbon (TC), total nitrogen (TN), ratio between TC and TN (C/N), total phosphorus (TP) concentrations at transition and 10 cm depth sediment sampled from different zones in the Manso reservoir. The OC mineralization rates in the sediment indicated that the allochthonous OM supply was an important fuel to the metabolism in the sediment of different zones of the Manso Reservoir. The stable isotope analysis of POM from different water column depths suggested different pools of OC in the zones, with isotopic signatures more enriched (allochthonous) in the river and transition and more depleted (autochthonous) in the dam. The $\delta^{13}C$ of POM of the first 2 cm of sediment followed the same pattern of the POM sources in the water, and reflected recent processes showing more $^{13}C$-enriched in the river and transition and more depleted (autochthonous) in the dam. The $\delta^{13}C$ was $-25.10 \permil$). Field observations also revealed the presence of blooms of the cyanobacteria M. aeruginosa near the dam, which may have contributed to the aquatic signature of the OM pool in the first 2 cm of the sediment. In all zones the 2 cm sediment depth grain sizes were classified largely as fine (8–16 μm) and very fine silt (4–8 μm) classes. Porosity ranged from 0.79 ± 0.10 at the 2 cm depth to 0.52 ± 0.10 at the 10 cm for all zones.

The organic carbon mineralization was different among the three zones with the highest average values in the transition (154.80 ± 33.50 mg C m$^{-2}$ d$^{-1}$), followed by the river (91.30 ± 28.70 mg C m$^{-2}$ d$^{-1}$) and the dam (51.60 ± 26.80 mg C m$^{-2}$ d$^{-1}$; Figure 3B). The bacterial abundance followed the same pattern as the mineralization rates as it was higher in the transition (5.10 ± 1.20 cells 10⁶ mL⁻¹; Figure 3C) and the river (4.30 ± 1 cells 10⁶ mL⁻¹). While no significant differences between bacterial abundance in the transition and river were found ($p = 0.44$), both zones were statistically different from the dam (3.30 ± 0.70, $p < 0.001$). The $p$CO$_2$ in the overlying water of the sediment was significantly different among the three zones ($p < 0.001$), gradually decreasing from the river to the dam, with highest values at the river (2570.60 ± 500 μatm) relative to the transition (2035.20 ± 10 μatm) and dam (1785.20 ± 100 μatm; Figure 3D). The $p$CO$_2$ in the surface water along the reservoir (data from Roland et al., 2010) also showed high values of $p$CO$_2$ on the river, but, with no statistical differences in the other zones ($p = 0.82$; Figure 3D). The organic carbon mineralization in the sediment was also positively related to the $p$CO$_2$ in the surface water of the reservoir ($p < 0.001$, $r^2 = 0.73$, Figure 4).

The bacterial abundance was positively related to OC mineralization ($p < 0.001$, $r^2 = 0.50$; Figure 5) in the overlying water of the sediment core.

DISCUSSION

The OC mineralization rates in the sediment indicated that the allochthonous OM supply was an important fuel to the metabolism in the sediment of different zones of the Manso Reservoir. The stable isotope analysis of POM from different water column depths suggested different pools of OC in the zones, with isotopic signatures more enriched (allochthonous) in the river and transition and more depleted (autochthonous) in the dam. The $\delta^{13}C$ of POM of the first 2 cm of sediment followed the same pattern of the POM sources in the water, and reflected recent processes showing more $^{13}C$-enriched in the river and transition zones, probably a result of the terrestrial material coming from the littoral areas, and more depleted in the dam, where the effect of littoral areas is lower and there is higher contribution of primary
FIGURE 3 | Characteristics of OM composition, OC mineralization, bacteria abundance and partial pressure of CO2 in the sediment of different zones of the Manso Reservoir. (A) Carbon isotope composition of the 2 and 10 cm of sediments sampled in different zones of the Manso Reservoir. (B) OC mineralization rates measured in the overlying water of sediment core incubations. The boundary of the box closest to zero indicates the 25th percentile, a line with the box marks the median, and the boundary of the box farthest from zero indicates the 75th percentile. Error bars above and below the box indicate the 90th and 10th percentiles and dark circles represent the outliers. (C) Mean and standard deviation of bacterioplankton abundance measured in the overlying water of the sediment cores incubations. Small letters represent the differences between the \( p \text{CO}_2 \) from overlaying water of the sediment cores incubations (black bars) and capital letters represent the differences between the \( p \text{CO}_2 \) measure on the surface water of the reservoir (gray bars). (D) Means and standard deviations of partial pressure of CO2 (\( p \text{CO}_2 \)) from the overlaying water of the incubation cores (black bars) and in the surface water of the reservoir (gray bars; data from Roland et al., 2010). In all panels different letters represent significant differences (one-way ANOVA, Tukey’s post hoc, \( p < 0.001 \)).

FIGURE 4 | Linear regression describing the relationship between OC mineralization rates in the sediment and the partial pressure of \( CO_2 (p\text{CO}_2) \) in the surface water of the reservoir (n = 33; \( p < 0.001 \)).

FIGURE 5 | Linear regression describing the relationship between bacteria abundance and OC mineralization rates from the overlying water of the incubation cores over time (n = 18; \( p < 0.001 \)).

producers (e.g., phytoplankton) in relation to the other zones (Kalff, 2002; Tremblay et al., 2004). Degradation of POM during sinking along the water column and in surficial sediment layers may cause changes in the isotopic signature (Meyers and Radir, 1993). Although, for a lake sediment of both autochthonous and allochthonous origin, the \( \delta^{13}C \) has been reported to increase by 0.4–1.5‰ during the initial degradation, with only minor changes after that period (Galman et al., 2009). This fractionation during initial degradation is comparatively small and will therefore only introduce a minor error in the calculated proportions of allochthonous POM. We observed a change in the POM signatures in the samples from the different water column depths of the dam zone, with more enriched signature in the bottom (27 m). However, the top 2 cm of sediment of the dam zone had a more
depleted signature. In this case, the depleted isotopic signature of the sediment may be related to past plankton blooms and previous mixing events that could have caused higher deposition of the phytoplankton from the water column. The 10 cm sediment layer was mostly allochthonous in the different zones, once the isotopically light phytoplankton debris may be preferentially degraded along the time. This layer can be seen as a reflection of previous conditions in the reservoir and is composed by older OM than the 2 cm.

The sediment sampled in 2 and 10 cm layers was mainly composed of fine and very fine silt, rich in carbon and nitrogen and poor in phosphorus compared to other water bodies (Lennon and Pfaff, 2005), what meets the mesotrophic condition of the system (Rangel et al., 2012). By the time of the survey, the Manso Reservoir had been in operation for 10 years and along its whole area, mainly in the dam, it was still possible to find a large number of dead trees remaining from the beginning of the impoundment. We believe the dead trees probably no longer contribute to mineralization in the sediment anymore, since they died more than 10 years ago and the remaining biomass was still there because of their very slow decay (Tremblay et al., 2004). Also, there was no visual contribution of aquatic macrophytes during the sampling, what indicates that phytoplankton and terrestrial material were, respectively, the most important autochthonous and allochthonous sources of carbon for the sediment mineralization during the sampling period.

A gradient of allochthonous OM contribution was found in the top 2 cm of sediment along the zones, with the greatest contribution in the river zone (56%), less in the transition zone (48%), and even less in the dam zone (7%). The OC mineralization followed the same pattern and increased with increasing inputs of allochthonous OM in the sediment. However, it is important to highlight that the origin and quality of the OM in the different zones may not be the same. For instance, the literature points out that allochthonous carbon reaching the rivers is mostly composed of terrestrial OM coming from the watershed, and this OM is more difficult to degrade and assimilate by aquatic bacteria (Kritzberg et al., 2005) and fungi (Groesser et al., 2007) communities, while the OM in the lacustrine area of the reservoir is more labile and is mostly released by primary producers in the water column (Tremblay et al., 2004; Forbes et al., 2012). However, in the river and in the transition zones, in spite of the OM being less degradable, there is higher OM deposition in comparison with the dam zone: as water flows become less turbulent upon entry of the river water into the reservoir, suspended particles will be rapidly deposited in the river zone and transition zone. We hypothesize that the higher amount of allochthonous OM deposition in the river and transition zones compensates for the low degradability of the allochthonous OM, because, with more OM available in the sediment, more OC is delivered to sediment bacteria and fungi, promoting higher OC mineralization rates in those zones. In addition, it is important to consider that OM sedimentation can also be influenced by the reservoir hydrodynamics, making it more difficult to trace OM source with a two source mixing model.

The Manso Reservoir is a typical tropical hydroelectric reservoir with a marked longitudinal gradient forming the river, the transition and the dam zones addressed in this study and first proposed by the reservoir zonation theory (see Thornton et al., 1990). The Manso Reservoir has complex hydrology, influenced by seasonal climatic conditions and by the river Manso dynamics. During the summer season (from late December to early March), when our sampling was performed, the Manso Reservoir is mostly stratified (Pacheco et al., 2011). However, sporadic heavy rain may occur in the region, mixing the entire water column of the reservoir. Studies made in the Manso reservoir during the same period of our sampling (Assireu et al., 2011; Pacheco et al., 2011) reported a plume inflow of the river Manso in the reservoir, allocating the river at the hypolimnion level. This inflow of the Manso River in the reservoir highlights possible interactions between the river water and the POM pools in hypolimnion of the dam zone. In fact, it supports the similar δ13C signatures of the POM found in the hypolimnion of dam (27 m) and the water samples of the river and the transition zones.

Heterotrophic bacteria were an important link between the allochthonous OM, the OC metabolism in the sediment and the release of carbon from sediment to water in the reservoir. In our survey we found a positive relationship between bacteria abundances and the OC mineralization rates (Figure 5). Similar relationships between bacterial abundance and OC mineralization in the sediment were found in a Chinese lake with different trophic conditions, where increasing contributions of allochthonous OC enhanced bacteria density, biomass, and diversity (Bai et al., 2012). Also, a positive relationship between OC mineralization in the sediments and bacteria biomass was found in a survey of eight boreal lakes (Gudasz et al., 2012). Those findings reinforce the importance of bacterial metabolic activities on the functioning of aquatic ecosystems (Pomeroy, 1974; Azam et al., 1983; Zehr, 2010) and call attention to the importance of biogeochemical processes developed by this community, such as respiration (Biddanda et al., 2001; Lennon and Pfaff, 2005) and the conversion of reduced forms of carbon into their biomass (Sherr and Sherr, 2002). Our findings highlighted that bacterial aerobic respiration was an important metabolic activity in the sediment of the reservoir and was fueled by the differential allochthonous OM delivery, as has been pointed out by the literature for lakes (Cole et al., 2009; Hanson et al., 2003; Kritzberg et al., 2004).

Evidence of allochthonous OC supporting metabolism in the water (Kritzberg et al., 2005; Cole et al., 2007; Karlsson et al., 2012) and in the sediment (Algsten et al., 2005; Kortelainen et al., 2006; Gudasz et al., 2010; Bai et al., 2012) of aquatic ecosystems has been reported in the literature, although the influence on OC mineralization in the sediments is still uncertain (Bai et al., 2012; Gudasz et al., 2012), especially for systems located in tropical areas and, in particular, man-made reservoirs (Bartin et al., 2009, Tranvik et al., 2009). Furthermore, in carbon budget models the sediment is mainly seen as a site of carbon storage (Cole et al., 2007; Tranvik et al., 2009), and the amount of carbon that this compartment mineralizes back to the water and to the atmosphere is poorly considered. The carbon mineralized in the sediment, together with other sources of CO2 from the water column, is a significant carbon source to the atmosphere; especially if we take in account the area occupied by reservoirs in the landscape is increasing worldwide (World Commission on Dams [WCD], 2000). For instance, in the three different zones of the Manso reservoir, we found an OC...
We estimate that the OC mineralization in the sediment can contribute up to 28% of the CO₂ emitted to the atmosphere. These findings reinforce the importance of the relation between the OC mineralization in the sediment and the CO₂ emissions, but also show that this relation is shaped by other factors that need to be better understood in order to arrive at more accurate estimates.

In summary, we found that the spatial variability in OC mineralization rates in the sediment may be linked to differences in allochthonous OM supply to the sediments, and mirrored in both the spatial variability of surface water CO₂ and bacterial abundances in the sediment. The OC mineralization rates in the sediment contribute significantly to the CO₂ emission from the water to the atmosphere. These results highlight that sediments should be considered in the assessment and management of carbon emissions from reservoirs to the atmosphere.

ACKNOWLEDGMENTS

We are grateful to Michael L. Paco, Jean-François Lapierre, Grace Wilkinson and Kyle Emery for the insights and ideas and for making language relates revisions. We are also very grateful to Jean P. Ometto and Marcelo Bernardes for isotope and CN analyses, to Vinícius J. Farajalla for use of his picoamperimeter and Alex E. Prat and Ricardo Poirley for sediment particle size analysis. Also, special thanks to Felipe S. Pacheco and Anderson V. Freitas for helping with field work and sediment sampling. This study was sponsored by FURNAS Centrais Elétricas S.A. and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Brazil (fellowships to Simone J. Cardoso and Fábio Roland) and CAPES, Foundation for the Coordination of Higher Education and Graduate Training (fellowship to Luciana O. Vidal). Finally, we want to thank the two reviewers and the special issue editor for their constructive comments.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any com- mercial or financial relationships that could be construed as a potential con- flict of interest.
Received: 17 January 2013; accepted: 09 April 2013; published online: 30 April 2013.
Citation: Cardoso, V., Vidal, F., Mendon- ça, R., Bade, L. and Roland, F. (2013). Spatial variation of sediment mineralization supports differential CO2 emissions from a tropical hydroelectric reservoir. Front. Microbiol. 4:101. doi: 10.3389/fmicb.2013.00101
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