

Dear editor,

We are grateful for all comments and suggestions.

Please find our answers in italic following Editor Comments (EC) and Reviewer Comments (RC):

EC1: Both reviewers had suggested a thorough English editing (a reviewer comment and your response shown below). Despite your efforts, there are still many sentences that need to be checked by a native speaker. Just to name a few examples here (pay attention to the parts in "..."):

Author Response (AR): Thank you for the constructive comments. Co-author Ward, a native English speaker, has thoroughly reviewed the manuscript for grammar and typos including the sections highlighted below.

Abstract - The Belo Monte hydropower complex located in the Xingu River is "one of the largest in the world" in terms of energy production capacity, and "the largest operating" as a run-of-the-river (ROR) hydroelectric system...

AR: We modified this sentence as follows: "The Belo Monte hydropower complex located in the Xingu River is the largest run-of-the-river (ROR) hydroelectric system in the world and has one of the highest energy production capacities among dams".

The FCO_2 (0.90 ± 0.47 and $1.08 \pm 0.62 \mu\text{mol m}^2 \text{d}^{-1}$ "to XR and IR respectively")...

AR: We modified this sentence as follows: " FCO_2 (0.90 ± 0.47 and $1.08 \pm 0.62 \mu\text{mol m}^2 \text{d}^{-1}$ for XR and IR, respectively) and pCO_2 ($1,647 \pm 698$ and $1,676 \pm 323 \mu\text{atm}$ for XR and IR, respectively) measured during the high water season were on the same order of magnitude as previous observations in other Amazonian clearwater rivers unaffected by impoundment for the same season".

However, the associated intermediate reservoir may "overcome" these emissions due to altered riverine characteristics....

AR: We modified this sentence as follows: "However, the associated Intermediate reservoir (IR) may exceed natural river emission rates due to pre-impounding vegetation influence".

Introduction – ...which "has" 5.1 Pg y^{-1} of carbon "terrestrially delivered" (Drake et al. 2018) and "???" about 2.1 Pg C annually "emitted" to the atmosphere (Raymond et al., 2013)...

AR: We modified this sentence as follows: "Inland waters cover an approximate area of 4.6 to 5 million km^2 or about 3% of Earth's land surface (Downing et al., 2006; Verpoorter et al. 2014). Roughly 5.1 Pg C y^{-1} of carbon is mobilized into inland waters from the terrestrial biosphere (Drake et al. 2018), of which about 2.1 Pg C y^{-1} is emitted to the atmosphere as CO_2 (Raymond et al., 2013)".

Great debate emerged "from" the Belo Monte hydropower project...

AR: We modified this sentence as follows: "Significant debate has surrounded the Belo Monte hydropower project since its initial survey in the 1980's due to the magnitude of the environmental impact and threat to local indigenous people".

The aim of this study is to "characterize" the CO_2 emissions from the Belo Monte reservoirs in the first two years post-impounding by assessing the spatial and temporal variability of CO_2 partial pressure (pCO_2) and carbon dioxide fluxes (FCO_2) in the XR and IR.

AR: We modified this sentence as follows: "The aim of this study is to evaluate CO_2 emissions from the Belo Monte hydropower complex during the first two years post-impoundment by assessing the spatial and temporal variability of CO_2 partial pressure (pCO_2) and carbon dioxide fluxes (FCO_2) in the XR and IR".

Discussion - Although pCO_2 and FCO_2 are correlated (Rasera, et al., 2013), "in this study was observed" some specific examples where k produces different fluxes even when pCO_2 was similar.

AR: We modified this sentence as follows: "Although pCO_2 and FCO_2 are typically correlated (Rasera, et al., 2013), in this study we observed several examples where variability in gas transfer velocities drive variable fluxes even when pCO_2 was fairly constant".

RC (reviewer comment; reviewer 2): 2. Language overall needs improvement. Too many commas used. Too many sentences that are confusing (many are mentioned in specific comments below).

AR: The language and style of the whole text was revised and improved.

EC2: Please define ROR at its first use in the introduction (...run-of-the-river (ROR) hydropower systems have smaller reservoirs...).

AR2: *We have updated this section with a brief description of ROR dams and their main characteristics (L59-61).*

EC3: As the two reviewers had commented earlier, specifying your research objective or hypotheses would help you transform the descriptive manuscript into a more focused one. There is still no clear goal statement in the abstract. Please consider specifying the major objectives (and hypotheses) in the following sentence: "We evaluated spatiotemporal variations of surface water CO₂ partial pressure (pCO₂), water-atmosphere CO₂ fluxes (FCO₂), and gas exchange coefficients (k₆₀₀) in the XR and IR during the first two years after the impoundment of the Xingu River."

AR3: *Thank you for the constructive comment. We have rewritten this sentence and added hypotheses both in the abstract (L7-9) and introduction (L93-95 and 97-100).*

EC4: Please specify what "altered riverine characteristics" are responsible for the observed change in CO₂ emissions from IR (Abstract – "However, the associated intermediate reservoir may overcome these emissions due to "altered riverine characteristics"). You could also make your point clearer in the concluding remark on ROR ("CO₂ emissions from ROR reservoirs to the atmosphere are in the range of natural Amazon rivers."), particularly in relation to your hypotheses. Do you mean that ROR does not alter CO₂ emissions?

AR4: *We have rewritten this sentence for clarity (L22-23). We have also added some additional concluding remarks to reinforce our hypotheses (L423-425).*

EC5: The technical detail questioned by the first reviewer (as shown below) is important, so please provide in Methods how you handled any dilution effect and checked the potential contamination by the remaining air in the evacuated vial. As the reviewer commented, typical vial evacuation procedures cannot remove the air inside 100%. Transferring a similar volume of air sample to the evacuated vial cannot guarantee that the vial has been removed of air 100%. You could easily test (and correct, if required) any potential left-over gas concentration by measuring CO₂ concentration after filling the evacuated vial with the same volume of N₂ gas as the typical volume of samples.

RC (reviewer 1): L150. How good was the evacuation? In my experience, it's very difficult to get a good vacuum, but probably 10% or more atmosphere will remain, which may dilute or contaminate your samples. Was this checked?

AR: *We are confident in our vial evacuation procedures and sample storage methods, which our team has extensive experience with. A vacuum pump was used to create a vacuum, which was confirmed since the volume of gas pulled from the syringe into the vial was similar to the vial volume without the needing to manually depress the syringe's plunger. We have modified the sentence for clarity (L171-172) and in addition evaluated our vial evacuation as requested. Vials were evacuated in two ways, 1) with an electric pump and 2) manually using a syringe and a three-way valve. In both methods we observed minimal contamination. With the vacuum pump method, the vials with N₂ added contained ~3% contamination by atmospheric air (410 ppm). With the syringe method there was ~2% contamination (Table 1). We do not feel that corrections to the data are needed with these minimal amounts of contamination.*

Table 1: Summary of CO₂ contamination test with pump and syringe evacuations.

	Pump	Syringe
Avg CO₂ conc (ppm)	14.04	8.2
Std Dv	3.17	1.58
CO₂ percent relative to atmosphere (%)	3.4	2
Sample n =	5	5

EC6: Spatial and temporal variations in pCO₂ and FCO₂ might be one of your key findings, but their descriptions are inconsistent or inaccurate, as sampled below. Please note that FCO₂ in the low-flow period was distinctively higher in IR. And differences in pCO₂ between XR and IR are not clear enough to say the difference definitely. Please double check and correct all the related descriptions throughout the manuscript.

Abstract – "Spatial heterogeneity was observed for pCO₂ during both low and high water seasons while FCO₂ showed significant spatial heterogeneity only during the high water period."

Results - Significant difference in FCO_2 was observed among environments sampled during high water season ($F_{3:28} = 7.94$, $R^2 = 0.43$, $p = 0.0089$) while the low water season had relatively homogeneous FCO_2 values ($F_{3:17} = 2.67$, $R^2 = 0.14$, $p = 0.08$) (Fig.4 and Table 3).

Discussion - The increase in pCO_2 during the high water season and can be related with the increased input of terrestrial organic and inorganic carbon into the rivers by surface run-off and subsurface flow of water...

During the low water season most of pCO_2 and FCO_2 decreased, especially in the river channel environment...

AR6: The manuscript has been revised to address these inconsistencies (L10-12; L18-19; L249-250; L263-265; L302-304; L322-324).

EC7: Adding to the previous comment on the key findings on spatiotemporal variations in pCO_2 and FCO_2 , Fig 3 needs to be improved in presentation quality. It is a very big and busy figure and there are also formatting errors (e.g., units not put in parentheses) and lacking information about the labels (e.g., UD, DD?). Please think about how to present all the plots in a more efficient way, by e.g. putting "High water" and "Low water" labels on top of all the plots and sharing "Environment" category labels only once at the bottom of all the plots. If you cannot show all results on a page, splitting them into two sub-figures or using a horizontal page format could be an alternative idea. Plotting over the same range on the vertical axis would make it easier to compare the high- and low-flow results. (e.g., -1000 to 3500 for the plots c and d).

AR7: All suggestions were added to the image and labels were made more detailed (L627-630).

EC8: In section 4.2., your explanations about the higher FCO_2 from IR during low water than in high water season were focused on the flooded OM as a potential source. What about the counteracting effect of phytoplankton uptake of CO_2 , which might have increased in the low water season, due to reduced turbidity and enhanced phytoplankton uptake of CO_2 ? Please refer to other studies that compared seasonal differences in reservoir primary production and CO_2 emissions; and provide a more balanced discussion of potential contributing factors for seasonal variations in the source and sink of CO_2 in reservoirs.

AC8: Thank you for the suggestion. We have added a new paragraph related to phytoplankton and IR CO_2 during the low water season as requested (L375-387).

EC9: Please provide more details on the several same variables in Table 3. It is difficult to understand how the same variables of pCO_2 and FCO_2 differ across the rows.

AC9: Updated as requested.

Relevant changes list:

Abstract:

Hypotheses added, pg. 2, lines 7-9.

Inconsistency review, pg.2, lines 10-12.

Inconsistency review, pg.2, lines 18-19.

Introduction:

Run-of-the-river reservoirs description, pg. 3, lines 59-61.

Results:

Inconsistency review, pg.8, lines 249-250.

Inconsistency review, pg.8, lines 263-265.

Discussion:

Inconsistency review, pg.9, lines 302-304.

Inconsistency review, pg.9, lines 322-324.

Discussion added, pg. 11, lines 375-387.

Conclusions:

Hypotheses concluding remark added, pg. 12, lines 423-425.

Figures:

Fig 3 description alteration, pg.16, lines 627-630.

Fig 3 alterations, pg.18.

Tables:

Table 3 alterations, pg. 23.

Marked-up manuscript:

Carbon dioxide (CO₂) concentrations and emission in the newly constructed Belo Monte hydropower complex in the Xingu River, Amazonia

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Keywords: run-of-the-river reservoir; greenhouse gas emission; tropical river damming.

Abstract

The Belo Monte hydropower complex located in the Xingu River is the largest run-of-the-river (ROR) hydroelectric system in the world and has one of the highest energy production capacities among dams. Its construction received significant media attention due to its potential social and environmental impacts. It is composed of two ROR reservoirs; the Xingu Reservoir (XR) in the Xingu's main branch and the Intermediate Reservoir (IR), an artificial reservoir fed by waters diverted from the Xingu River with longer water residence time compared to XR. We aimed to evaluate spatiotemporal variations of CO₂ partial pressure (pCO₂) and CO₂ fluxes (FCO₂) during the first two years after the Xingu River impoundment under the hypothesis that each reservoir has contrasting FCO₂ and pCO₂ as vegetation clearing reduces flooded areas emissions. Time of the year had a significant influence on pCO₂ with the highest average values observed during the high water season. Spatial heterogeneity throughout the entire study area was observed for pCO₂ during both low and high water seasons. FCO₂, on the other hand only showed significant spatial heterogeneity during the high water period. FCO₂ (0.90 ± 0.47 and $1.08 \pm 0.62 \mu\text{mol m}^2 \text{d}^{-1}$ for XR and IR, respectively) and pCO₂ ($1,647 \pm 698$ and $1,676 \pm 323 \mu\text{atm}$ for XR and IR, respectively) measured during the high water season were on the same order of magnitude as previous observations in other Amazonian clearwater rivers unaffected by impoundment during the same season. In contrast, during the low water season FCO₂ (0.69 ± 0.28 and $7.32 \pm 4.07 \mu\text{mol m}^2 \text{d}^{-1}$ for XR and IR, respectively) and pCO₂ (839 ± 646 and $1,797 \pm 354 \mu\text{atm}$ for, XR and IR respectively) in IR were an order of magnitude higher than literature FCO₂ observations in clearwater rivers with naturally flowing waters. When CO₂ emissions are compared between reservoirs, IR emissions were 90% higher than values from the XR during low water season, reinforcing the clear influence of reservoir characteristics on CO₂ emissions. Based on our observations in the Belo Monte hydropower complex, CO₂ emissions from ROR reservoirs to the atmosphere are in the range of natural Amazonian rivers. However, the associated reservoir (IR) may exceed natural river emission rates due to the pre-impounding vegetation influence. Since many reservoirs are still planned to be constructed in the Amazon and throughout the world, it is critical to evaluate the implications of reservoir traits on CO₂ fluxes over their entire life cycle in order to improve estimates of CO₂ emissions per KW for hydropower projects planned for tropical rivers.

1 Introduction

Rivers and streams are no longer considered passive pipes where terrestrial organic matter (OM) travels unchanged from land to sea (Cole et al., 2007). The OM transported by inland waters may be converted to carbon dioxide (CO₂) or methane (CH₄) and escape to the atmosphere as gaseous emissions (Battin et al., 2009; Ward et al., 2013). Inland waters cover an approximate area of 4.6 to 5 million km² or about 3% of Earth's land surface (Downing et al., 2006; Verpoorter et al. 2014). Roughly 5.1 Pg C y⁻¹ of carbon is mobilized into inland waters from the terrestrial biosphere (Drake et al. 2018), of which about 2.1 Pg C y⁻¹ is emitted to the atmosphere as CO₂ (Raymond et al., 2013). Despite the relatively small area covered by inland waters, their carbon emissions offset the ocean's carbon sink (1.42 ± 0.53 Pg C y⁻¹) (Landchützer et al., 2014).

Channel impoundment promotes several changes in river properties such as surface wind shear, water temperature, discharge and turbulence, and organic and inorganic sediment input (St. Louis et al., 2000). These changes alter the microbial community structure and biogeochemical processes in the water column and riverbed sediments, with consequent impacts on the dissolved carbon load, production, and eventual release to the atmosphere as CO₂ (Battin et al., 2008). The intense decomposition of OM contained in flooded soils, in addition to the consumption of allochthonous OM deposited in the reservoir may lead to an increase of the CO₂ production, and outgassing, particularly during the first years of channel impoundment (Guérin et al., 2006). Longer water residence time and reduction in water flow velocity, on the other hand, may increase light penetration depth due to the deposition of suspended sediments, possibly counterbalancing those emissions due to higher CO₂ uptake by primary producers (Duarte and Prairie, 2005). Alternatively, this condition may stimulate OM decomposition via photo-oxidation that is favored by increased light absorbance (Miller and Zepp, 1995) and microbial priming effects driven by interactions between allochthonous and autochthonous carbon sources (Ward et al., 2016).

Some of the hydropower dams' impacts may be minimized according to the dam design. Run-of-the-river (ROR) hydropower systems maintain a similar flow to a natural river (Csiki and Rhoads, 2010), which generates smaller reservoirs that operate according to seasonal variations in water levels (Egré and Milewski, 2002). The Belo Monte hydropower complex in the lower Xingu River operates as ROR and it is the largest hydropower plant in the Amazon. It ranks third in the world in terms of installed capacity (11,233 MW), but with high variation in energy production throughout the year due to the high seasonality of the water discharge of the Xingu River (Brasil, 2009a). Significant debate has surrounded the Belo Monte hydropower project since its initial survey in the 1980s due to the magnitude of the environmental impact and threat to local indigenous people (Fearnside, 2006). These discussions lasted at least 20 years and resulted in a series of changes and revisions to the initial project (Fearnside, 2006). Nevertheless, the Belo Monte hydropower complex had its reservoirs filled in 2015 (MME, 2011), amid strong environmental controversies (Fearnside, 2017), including uncertainties in estimates of greenhouse gas (GHG) emissions (Fearnside, 2002). As such, alterations in the natural carbon cycling in the aquatic environments under direct and indirect influence of the Belo Monte hydropower facilities may result in significant impacts on the regional carbon budget. This is a critical question to evaluate the GHG emissions related with hydroelectricity produced from impoundment of large tropical rivers.

Hundreds of new hydropower reservoirs are currently under construction or planning stages in tropical South America, Africa, and Asia (Winemiller et al., 2016), and many of them may be ROR reservoirs. However, to our knowledge, estimates of GHG emissions from ROR reservoirs only include measurements performed several decades after the construction of a small temperate reservoir in Switzerland, or obtained through modeling for tropical reservoirs in Brazil (DelSontro et al., 2010; Faria et al., 2015). Therefore, most of the GHG emissions estimates available in the literature are for storage reservoirs, but also with measurements representative of

several years (> 10 years) after the construction of the hydropower dams (Kemenes et al., 2011; Lima et al., 2002). Exceptions are a tropical (Abril et al., 2005) and a boreal storage reservoirs (Teodoru et al. 2011) studied since impoundment. These studies showed that CO₂ emissions were higher during the first years of impoundment. Thus, estimates of GHG emissions immediately after river impoundment are critical determining the overall carbon balance of the hydroelectricity system lifetime.

The Belo Monte hydropower plant has two reservoirs operating under ROR conditions. The Xingu Reservoir (XR) was formed by the impoundment of the Xingu River channel, which has waters diverted to feed the Intermediate reservoir (IR), created by the impoundment of a valley artificially connected to the left margin of the Xingu River. Although both reservoirs are considered to be ROR, they differ in water residence time and type of flooded vegetation and substrates. Flooded areas in the XR correspond mainly to seasonally flooded forest, but upland forest in marginal areas was also flooded locally. Vegetation was removed from most of the flooded areas, but part of the flooded forest islands in the XR was not cleared. On the other hand, the IR flooded large swaths of upland forest and pasture areas and its water residence time is higher than in the XR.

The aim of this study is to evaluate CO₂ emissions from the Belo Monte hydropower complex during the first two years post-impoundment by assessing the spatial and temporal variability of CO₂ partial pressure (pCO₂) and carbon dioxide fluxes (FCO₂) in the XR and IR. This evaluation is crucial to understand GHG emissions from reservoirs in the eastern Amazon, a tropical region poised to add 153 more hydropower facilities in the coming decades (Aneel, 2019). Considering the physiographic and hydraulic differences of the XR and IR, we hypothesize that (1) the two Belo Monte reservoirs have contrasting CO₂ partial pressure (pCO₂) and carbon dioxide fluxes to the atmosphere (FCO₂); and (2) the clearing of forest vegetation significantly reduces the emissions from areas flooded by the reservoirs during the first two years after channel impoundment.

2 Material and methods

2.1 Study area

The Xingu River is the second largest clearwater tributary of the Amazon River. It drains an area of 504,000 km² and flows from central Brazil (15°S) to the lower Amazon River in eastern Amazon (3°S) (Latrubesse et al., 2005; Brasil, 2009b). Clearwater rivers are characterized by neutral to slightly alkaline pH, and low concentration of suspended sediment, with high light penetration (Sioli, 1984). The climate of the region has high seasonality, with the rainy period usually starting in December, extending until May and rainfall peaking in March and April (Inmet, 2017). The dry season occurs from June to November, with the driest months occurring in September and October (Fig.1). The average monthly rainfall and temperature were 188 ± 145 mm and 27.5 ± 1.0 °C, respectively (10 year average from 2004 to 2014) (Inmet, 2017). In accordance with the rainfall regime, river discharge is marked by strong seasonality with the low water season occurring from September to November, and the high water season from March to May. The historic average discharge of the Xingu River in the sector of the Belo Monte hydropower complex for the period from 2004 to 2014 was 1,408 ± 513 m³ s⁻¹ during the low water season and 18,983 ± 9,228 m³ s⁻¹ in the high water season (Fig.1) (ANA, 2017). The dominant land cover in the middle and lower Xingu watershed is tropical rainforest, although agriculture and deforested areas occur mainly in the south and southwest areas of the basin and close to Altamira, the largest city near the Belo Monte hydropower complex (Brasil, 2009b). The studied area ranges from the lower Iriri River, the largest tributary of the Xingu River, to downstream of the sector known as “*Volta Grande do Xingu*” (Xingu Great Bend), nearby the municipality of Vitória do Xingu (Fig. 2).

The construction of Belo Monte started in 2011, and reservoirs (Fig. 2) were flooded in 2015 (Brasil, 2011). The studied reservoirs have maximum depths reaching 20.5 m in the XR and 58.3 m in the IR, although both dams

have similar intake depths of about 15-20 m. The Pimental dam in the Xingu River channel hosts 6 turbines and floodgates that regulate the water flow from the XR through a 28 km channel to feed the IR formed by the Belo Monte dam. The latter contains the main power station with 18 turbines summing 11,000 MW of potential energy production, equivalent to 97% of the total installed power capacity of 11,233 MW (Brasil, 2009a; 2009c).

Together the reservoirs occupy an area of 516 km². The XR extends over an area of 382 km² (Brasil, 2009b) from which 94 km² corresponds to land permanently or seasonally flooded, similar to the natural water level condition during the high water season (Fig.2). It is estimated that 52% of the total area flooded by the XR was not cleared of vegetation (Norte Energia, 2015). Differently, the IR occupies an area of 134 km² and large flooded areas of pasture and upland non-flooded forest (locally called "*terra firme* forest"). Contrary to the XR, the IR flooded area was totally vegetation cleared previously to reservoir filling (Norte Energia, 2015). Waters diverted from the XR return to the Xingu River channel after flowing around 34 km over flooded lands in the IR (Fig.2) (Brasil, 2009c; 2009a). The sector of the Xingu River between the outflows of the XR and IR, including part of the Xingu Great Bend, has reduced water discharge and flow controlled by operational conditions of the Belo Monte hydropower complex.

The residence times (RT) of the XR and IR were calculated based on the maximum potential discharge established for each dam (Brasil, 2009b). We assumed that the sum of both discharges is the total discharge in an extreme scenario, and therefore equivalent to the fraction of the total river discharge passing through each dam. The fraction of discharge was combined with the historical average annual discharge of the Xingu River (ANA, 2017), similarly to Faria et al. (2015), using the following Eq. (1):

$$RT = \frac{V}{Q} \quad (1)$$

Where RT is the water residence time given in seconds, and later converted into days, V is the reservoir volume in m³ and Q is the volumetric discharge in m³/s. The XR has RT of 3.4 days while RT in the IR is 20.2 days. This difference was used to test if the RT plays a significant role in the CO₂ emissions in ROR reservoirs.

2.2 Carbon dioxide partial pressure (pCO₂) and CO₂ flux (FCO₂) to the atmosphere

In order to cover zones with different flooded substrates and hydrologic characteristics, the sampling sites included the original river channel within the XR, flooded lands (forest and pasture) of both reservoirs, and upstream and downstream river channel sections outside the influence of the reservoirs (Fig.2). Four classes were considered to evaluate the spatial heterogeneity of FCO₂:

- (I) unaffected river channel: sites located in the channels of the Xingu and Iriri Rivers outside reservoir areas, in sectors upstream and further downstream of the reservoirs;
- (II) main channel: Xingu River main branch within the reservoir area (XR);
- (III) flooded areas: lands of pasture and upland forest formerly non-flooded during the high water level season and seasonally-flooded forested islands that were permanently inundated by both reservoirs;
- (IV) downstream of the dams: sites immediately downstream of the dams that receive the water discharge from turbines of the XR and IR dams.

Sampling sites near the confluence of the Xingu and Iriri Rivers (sites P1 and P3, Table 1) were used as reference sites for areas without direct influence of the reservoirs. The sites further downstream of the dams (P20 and P21) were characterized to investigate the influence of the reservoirs on the downstream FCO₂ (Table 1).

During the year of 2017 (high and low water level seasons), values of pCO₂ in the water column were obtained using the headspace equilibration method according to Hesslein et al. (1991). The pCO₂ was measured following three depth classes (Table 1): (I) near bottom: 0.5-1.0 m above the river or reservoir bottom; (II) 60%: at 60% of

total water depth; (III) surface: up to 0.3 m of water depth. Sites shallower than 7.5 m were sampled only at 60 % of the total depth. Polycarbonate bottles of 1 L were overflowed three times their volume with water drawn by a submersible pump. The bottle was closed with rubber stopper adapted with tubes and luer-lock valves, allowing the simultaneous injection of 60 mL of atmospheric air and withdrawal of the same volume of water using syringes, creating the headspace. The bottles were shaken for three minutes to equilibrate the gas in the water and headspace air. Water was then re-injected simultaneously to the collection of the headspace air. Atmospheric air samples were also collected using 60 ml syringes for corrections related with atmospheric CO₂. All gas samples were transferred from syringes to glass vials that were pre-capped with butyl rubber stoppers and evacuated with a vacuum pump. pCO₂ was measured using a Picarro® G2201-i cavity ring-down spectroscopy (CRDS) and concentration calculations were based on Wiesenburg and Guinasso (1979).

Diffusive CO₂ emission was measured with floating chambers during 2016 and 2017 high water seasons using an infrared gas analyzer (IRGA) LI-COR® Li820 coupled to a 7.7 L opaque (covered with reflexive aluminum tape) floating chamber with 0.08 m² of area and 11.7 cm of height. The analyzer captures the change in CO₂ concentration inside the chamber by constant recirculation driven by a micro-pump with an air flow of 150 mL min⁻¹. For each site, three consecutive deployments were made for five minutes each from a drifting boat to avoid extra turbulence. During the 2017 low water season CO₂ mini-loggers (Bastviken et al., 2015) placed inside 6 L opaque (covered with reflexive aluminum tape) floating chambers with 0.07 m² of area and 10.5 cm of height were used to measure CO₂ fluxes. Sensors were placed inside the two chambers and deployed simultaneously during 20-30 minutes with a logging frequency of 30 seconds. CO₂ fluxes from water to the atmosphere were calculated according to Frankignoulle et al. (1998):

$$FCO_2 = \left(\frac{\delta pCO_2}{\delta t} \right) \left(\frac{V}{RT_{\kappa}A} \right), \quad (2)$$

The CO₂ flux (FCO_2) in mol CO₂ m⁻² s⁻¹ is given by the changes in pCO₂ inside the chamber during the deployment time ($\delta pCO_2/\delta t$, $\mu\text{atm s}^{-1}$), taking into account the chamber volume (V , m³), the universal gas constant (R , atm m³ mol⁻¹ K⁻¹), water temperature (T , K) and the area covered by the chamber (A , m²). Measurements were discarded when the R² of the linear relation between pCO₂ and time ($\delta pCO_2/\delta t$) were lower than 0.90 ($R^2 < 0.90$) or had negative FCO_2 values with surface pCO₂ higher than atmospheric pCO₂ measured on site. The gas sampling survey (Fig.2 and Table 1) occurred during the high water level season in April 2016, May 2017 and during the low water level season in September 2017. Due to technical difficulties, pCO₂ data were only collected during 2017 and FCO_2 samplings of 2017 were made with different equipment.

2.3 Gas transfer velocity (k_{600})

The air-water gas transfer coefficient k (cm h⁻¹) of CO₂ was estimated based on the surface water CO₂ concentration inside the floating chamber by Eq. (3):

$$k = \frac{V}{A \cdot \alpha} \ln \left(\frac{pCO_{2w} - pCO_{2i}}{pCO_{2w} - pCO_{2f}} \right) / (t_f - t_i), \quad (3)$$

Where V and A are the chamber volume (cm³) and area (cm²), α is the Ostwald solubility coefficient (dimensionless), t is the time (h), and the subscripts w , i and f refers to the partial pressure in the surface water, and initial and final time inside the chamber, respectively. Ostwald solubility coefficient was calculated from K_0 as described by Wanninkhof (2009). Finally, k values were normalized to k_{600} following the Eq. (4) and (5) (Alin et al., 2011; Jähne et al., 1987; Wanninkhof, 1992):

$$k_{600} = k_T \left(\frac{600}{Sc_T} \right)^{-0.5}, \quad (4)$$

Where k_T is the measured k value at in situ temperature (T), Sc_T is the Schmidt number calculated from temperature and 600 is the Schmidt number for temperature of 20° C. The Schmidt number is calculated as a temperature (T) function:

$$Sc_T = 1911.1 - 118.11 T + 3.4527 T^2 - 0.041320 T^3, \quad (5)$$

2.4 Physical-chemical characteristics

Depth profiles with a measurement interval of 1m were done for water temperature, pH, dissolved oxygen (DO) and conductivity using a multiparameter probe (EXO2®, YSI). During the high water in 2016 and 2017 sampling campaigns, technical challenges prevented measurement of pH, dissolved oxygen (DO), and conductivity during the 2017 low water sampling. For statistical analysis these measurements were selected following the same water depth classes applied to pCO₂ measurements (surface, 60% and near the bottom). Additionally, air temperature and wind speed were measured at the same time of chamber deployments with a handheld meteorological meter (Kestrel® 5500) positioned at 2 m above the water surface.

2.5. Statistical analysis

Statistical analyses were performed to check the correlation among CO₂ variables (FCO₂ and pCO₂) and water column characteristics (pH, dissolved oxygen (DO) and water temperature) and to evaluate the spatial and seasonal variation of FCO₂, pCO₂ and k_{600} . Normality and heterogeneity of variance were not achieved by Shapiro-Wilks and Bartlett tests, respectively. Thus, non-parametric and multivariate statistical tests were used. The seasonal and spatial variability of FCO₂, pCO₂, k_{600} and wind velocity were tested by PERMANOVA analysis (Anderson, 2001), a multivariate test that compares group variance (within and between) through a distance matrix using permutation to achieve p-value. The Euclidian index was used as distance method and 9999 permutations to run the analysis. The FCO₂ statistics were assessed separately by season due to the different sampling methods. The Spearman correlation test (Zar, 2010) was performed to evaluate the correlation between FCO₂ versus pCO₂, FCO₂ versus wind speed, k_{600} versus wind speed and pCO₂ versus physical-chemical variables (pH, DO and water temperature). All statistical analyses were performed in R (R Development Team Core, 2016) using the Vegan package (Oksanen et al., 2017) and Statistica (Statsoft 8.0) using 5% (0.05) as critical alpha for significance.

3 Results

3.1 Temporal and spatial variability in pCO₂ and FCO₂

Mean pCO₂ from areas upstream and downstream of the dams was 1,163 ± 660 μatm. Based on 2017 data pCO₂ values differed significantly between seasons ($F_{1:56} = 9.77$, $R^2 = 0.09$, $p = 0.0045$) with higher pCO₂ in the high water season (1,391 ± 630 μatm) compared to the low water period (976 ± 633 μatm) (Fig. 3a). The type of environment also had a significant role in pCO₂ distribution throughout the area affected by the reservoirs ($F_{3:56} = 13.36$, $R^2 = 0.37$, $p = 0.0002$). During the high water season the highest average pCO₂ was observed downstream of the dams. In contrast, during the low water season the highest average pCO₂ values were observed in the reservoirs over the flooded areas. Unaffected river channel categorized areas had the lowest pCO₂ in both seasons (Fig.3).

On average, across all seasons bottom water had higher pCO₂ (1,269 ± 689 μatm) compared to surface water (998 ± 613 μatm) ($F_{2:56} = 4.06$, $R^2 = 0.07$, $p = 0.0261$) (Table 2). Surface pCO₂ was positively correlated with FCO₂

both during the high water ($r = 0.80$; $p = 0.0009$) and low water ($r = 0.71$; $p = 0.012$) seasons (Fig.3). Bottom water $p\text{CO}_2$ showed correlation with FCO_2 only during the high water season ($r = 0.68$; $p = 0.042$) while data from low water season have non-significant correlation ($r = 0.45$; $p = 0.16$) (Table 3). Average FCO_2 for all sites sampled during 2016 and 2017 high water seasons was $1.38 \pm 1.12 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ with similarity between years ($F_{1:28} = 0.09$, $R^2 = 0.01$, $p = 0.7790$). Therefore, FCO_2 data from the high water seasons of 2016 and 2017 were treated as a single data set for the further calculations.

The highest ($12.00 \pm 3.21 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) and lowest ($-0.52 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) FCO_2 values were observed during the low water season (Fig.3). Significant difference in FCO_2 was observed among environments sampled during high water season ($F_{3:28} = 7.94$, $R^2 = 0.43$, $p = 0.0089$) while the low water season was not statistically different ($F_{3:17} = 2.67$, $R^2 = 0.14$, $p = 0.08$) (Fig.4 and Table 3) considering whole study area. The highest ($2.89 \pm 1.74 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) and lowest ($0.84 \pm 0.42 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) average FCO_2 , respectively, occurred in sectors downstream of the dams and in flooded areas sampled during the high water season. Negative CO_2 fluxes were exclusively observed during the low water season in the river channel (Table 2 and Fig.4).

In addition to the spatial heterogeneity, pre-existing vegetation cover influenced $p\text{CO}_2$ and FCO_2 in the XR. Areas previously covered by pasture, upland forest and seasonally flooded forest had significantly different CO_2 concentrations. Sites that were 90 and 25 km downstream of the Pimental (XR) and Belo Monte (IR) dams, respectively, had lower $p\text{CO}_2$ and FCO_2 values compared to areas within the reservoirs.

3.2 $p\text{CO}_2$ and FCO_2 in the reservoirs

The spatial variability of $p\text{CO}_2$, FCO_2 and k_{600} were assessed within and between reservoirs. We evaluated the total CO_2 emissions from reservoirs by grouping flooded areas and river channel of the XR for comparison with flooded areas from the IR. FCO_2 and $p\text{CO}_2$ presented higher values in the XR during the high water season, while the opposite pattern occurred in the IR (Table 2).

XR and IR seasonal variation was not significant even when high water ($F_{1:25} = 2.28$, $R^2 = 0.03$, $p = 0.1536$) and low water ($F_{2:30} = 0.77$, $R^2 = 0.03$, $p = 0.4684$) seasons were evaluated separately (Table 3). $p\text{CO}_2$ also showed no significant difference between XR and IR ($F_{3:56} = 0.34$, $R^2 = 0.009$, $p = 0.8170$). As observed for $p\text{CO}_2$, there was no effect of reservoir type on FCO_2 variability during high water conditions ($F_{1:28} = 0.32$, $R^2 = 0.01$, $p = 0.5811$). In contrast, FCO_2 during low water condition differed significantly between XR and IR ($F_{1:17} = 34.07$, $R^2 = 0.61$, $p = 0.0003$). The IR had the highest average FCO_2 ($7.32 \pm 4.06 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) during the low water season while the XR presented low FCO_2 ($0.69 \pm 0.28 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$). Despite variations in FCO_2 and $p\text{CO}_2$, no difference on k_{600} was observed between reservoirs during the high water ($F_{1:9} = 0.02$, $R^2 = 0.01$, $p = 0.9180$) or low water seasons ($F_{1:12} = 5.46$, $R^2 = 0.45$, $p = 0.0900$) (Table 3).

3.3 Gas transfer velocity (k_{600})

The average k_{600} was 17.8 ± 10.2 and $34.1 \pm 24.0 \text{ cm h}^{-1}$ for high and low water seasons, respectively, without significant spatial heterogeneity across environments ($F_{3:9} = 2.42$, $R^2 = 0.70$, $p = 0.2043$ and $F_{3:12} = 0.12$, $R^2 = 0.03$, $p = 0.9441$, respectively). Values of k_{600} are correlated with wind speed ($r = 0.73$; $p = 0.016$) during the high water season, although this observation was not significant during the low water season ($r = 0.53$; $p = 0.067$).

Wind speeds ranged from 0.7 to 4.8 m s^{-1} , considering measurements for all sites and sampling periods. Highest average wind speed was observed on the river channel environment while downstream of the dams had the lowest (3.21 ± 0.89 and $1.66 \pm 0.88 \text{ m s}^{-1}$, respectively) (Table 4). In contrast to k_{600} , wind speed varied significantly across environments ($F_{3:37} = 6.13$, $R^2 = 0.23$, $p = 0.0034$), including variation between the XR and IR ($F_{2:37} = 8.40$, $R^2 = 0.21$, $p = 0.0016$).

3.4 Physical-chemical characteristics

The air temperatures at the studied sites varied between 27.5 and 33.8 °C during sampling in both seasons, with the maximum temperatures registered during the low water period. The surface water temperature ranged from 29.2 to 32.7 °C, with maximum temperature registered during the high water period. The lowest (6.60 ± 0.26) and highest (6.81 ± 0.21) average pH values, in waters of flooded areas and river channel (Table 4). The water column was relatively well-oxygenated in all studied environments, reaching average DO concentration up to $7.28 \pm 0.73 \text{ mg L}^{-1}$ in the unaffected river channel and lowest concentration in flooded areas ($5.44 \pm 2.00 \text{ mg L}^{-1}$) (Table 4). Water conductivity varied from 20.60 to 38.30 $\mu\text{S cm}^{-1}$ in the studied environments, with the highest average value ($31.60 \pm 8.63 \mu\text{S cm}^{-1}$) recorded in flooded areas and lowest value ($29.30 \pm 4.85 \mu\text{S cm}^{-1}$) in areas downstream of the dams (Table 4). In the study sites, pCO_2 is negatively and strongly correlated with pH and DO (Table 3). Correlation between pCO_2 and water temperature was absent while FCO_2 was positively correlated with wind speed (Table 3).

4 Discussion

4.1 Temporal and spatial variability in pCO_2 and FCO_2

Although pCO_2 and FCO_2 are typically correlated (Rasera, et al., 2013), in this study we observed several examples where variability in gas transfer velocities drive variable fluxes even when pCO_2 was fairly constant. It has been shown that the amount of CO_2 in the water column and CO_2 emissions from Amazon rivers to the atmosphere vary significantly among seasons with higher fluxes generally observed during the high water season (Alin et al., 2011; Rasera et al., 2013; Richey et al., 2002; Sawakuchi et al., 2017). We observed significant variability in pCO_2 between high and low water seasons, as well as in terms of physiographic-hydrologic environment, which influenced FCO_2 values. High pCO_2 production during the high water season can be related to increased input of terrestrial organic and inorganic carbon into the rivers by surface run-off and subsurface flow of water (Raymond and Saiers, 2010, Ward et al., 2017). Remaining vegetation and soils are the major sources of OM in areas flooded by hydropower reservoirs that sustain high rates of CO_2 production during the initial years of impoundment (Guérin et al., 2008). In addition, the seasonal input of autochthonous and allochthonous organic material deposited in the reservoirs with higher water RT may result in seasonal pCO_2 and FCO_2 variability.

The oversaturation in CO_2 observed for XR and IR during high water conditions was spatially heterogeneous (Table 2). In the river channel environment of the XR pCO_2 decreased as FCO_2 increased and the contrary occurred in flooded areas. This is perhaps due to the main OM source to the XR being standing vegetation associated with remnant flooded forests and pasture, which agrees with higher pCO_2 from flooded areas. Flooded vegetation is recognized to be the main source of OM in reservoirs, playing an important role in the CO_2 production and creating gradients of reservoir CO_2 emissions (Roland et al., 2010; Teodoru et al., 2011). The different characteristics including vegetation clearing, variation on hydrodynamic conditions, water depth (Teodoru et al., 2011, Roland et al., 2010) and OM availability (Cardoso et al. 2013) may explain the difference in the observed FCO_2 and pCO_2 values.

About 59% of the XR area is the original channel of the Xingu River. However, the water velocity under reservoir conditions is slower than in channel sectors outside the effect of dams and regulated by spillways of the Pimental dam. FCO_2 measured upstream of the XR during the high water season in a sector where the channel is flowing under natural conditions (Iriri River sites) was significantly higher than in the XR sector (Table 2). CO_2 concentrations in the water column may decrease, especially on upper water layers, in response to the increased photosynthetic uptake of CO_2 during lower rainfall periods (Amaral et al., 2018). During the low water season pCO_2 and FCO_2 decreased resulting in homogeneous FCO_2 likely due to photosynthetic activity in all

environments, with exception of the IR (Table 2). In addition, CO₂ undersaturation relative to the atmosphere and observed CO₂ uptake may be attributed to elevated primary productivity, which is facilitated due to the high light penetration and has been similarly observed in previous studies in Amazonian floodplain lakes and other clearwater rivers during the low water season (Amaral et al., 2018, Rasera et al 2013, Gagne-Maynard et al., 2017). The occurrence of negative CO₂ fluxes was observed only in the unaffected river channel at the furthest downstream site. This pattern can be related to the downstream decrease in suspended sediments due to increased sediment deposition in the reservoirs. CO₂ fluxes in the XR and IR may also be favored by wind activity due to larger fetch for wave formation within the reservoirs. Wave action could favor degassing as well as the increase in suspended sediments that reduce light penetration and photosynthetic activity. These processes may also result in the observed decrease in pCO₂ and FCO₂ downstream of the dams. The site downstream of IR (P21) is within the river extent (< 30 km) that could still be affected by the reservoir similar to observations downstream of the Amazonian Balbina reservoir (Kemenes et al., 2016). However, the XR should only have a minor effect on the downstream site due to its longer distance from the dam outflow (90 km) and the presence of many large rapids and waterfalls in the Volta Grande region, quickly degassing the dissolved CO₂ coming from the upstream reservoir. The decrease in pCO₂ and FCO₂ persisted in areas downstream of the Belo Monte reservoirs as indicated by measurements performed in this study during the high water and low water seasons. The river reaches downstream of the Belo Monte dams have CO₂ emissions similar to observations from previous studies with emissions also decreasing downstream (Abril et al. 2005; Kemenes et al. 2011).

River reaches downstream of tropical storage reservoirs FCO₂ measured in the Sinnamary River downstream of the Petit Saut reservoir in French Guiana was $10.49 \pm 3.94 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (Guérin et al. 2006), which is more than three times our average downstream FCO₂ ($2.89 \pm 1.74 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) during high water season (Table 2). Although the Petit Saut dam has a smaller reservoir its turbine intake is hypolimnetic (Abril et al., 2005), capturing CO₂-rich bottom waters that increase downstream emissions through turbine passage (Guérin et al., 2006; Kemenes et al., 2011; 2016). Alternatively, the Belo Monte hydropower facility operates as ROR and has waters mixed without stratification and lower CO₂ oversaturation than in the Petit Saut reservoir likely due to vegetation clearing.

4.2 pCO₂ and FCO₂ on Belo Monte reservoirs

The IR presented an average FCO₂ about 90% higher than values observed in the XR during low water season. Although the XR has a larger surface area than the IR (excluding the water diversion channel), most of it corresponds to the natural river channel under a hydraulic condition similar to the high water season with less flooded areas, restricted to narrow upland margins, but including flooded large forested islands. On the other hand, the higher flooded area extension of the IR was previously covered by upland forest and pasture resulting in higher organic matter availability. CO₂ emissions from the IR during the low water season were even above the range of emissions observed in storage reservoirs in the Amazon such as the Tucuruí hydropower complex, built in 1984 on the clearwater Tocantins River (Lima et al. 2002). After more than 30 years the Tucuruí reservoir still contributes with $3.61 \pm 1.62 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ to the atmosphere (Lima et al., 2002). In comparison to the XR (FCO₂ = $0.69 \pm 0.28 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) the Tucuruí reservoir has higher FCO₂. However, this is three times lower than FCO₂ ($7.32 \pm 4.06 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) measured in the IR during the low water season.

Some characteristics of the Tucuruí reservoir such as the lack of vegetation clearing prior to flooding and large reservoir area contribute to its relatively high GHG emissions (Fearnside, 2002). It must be considered that XR had partial vegetation removal in some areas, while IR had its entire landscape cleared. FCO₂ and pCO₂ measured during high water conditions in the Belo Monte reservoirs area (Table 2) were in the same order of magnitude of emissions measured in Amazon clearwater rivers unaffected by impoundment including the

Tapajós River, which has hydrologic conditions similar to the Xingu River (Table 5) (Alin et al., 2011; Rasera et al., 2013; Sawakuchi et al., 2017). The vegetation clearing possibly maintained the low CO₂ emissions on both reservoirs during high water. However, the CO₂ emission from the IR is higher during low water, exceeding the fluxes of the Amazon River (Table 2) (Table 5). When analyzed separately, average FCO₂ values observed for XR and IR overcome these natural emissions. Based on the Belo Monte case, ROR dams are a CO₂ source to the atmosphere similar to natural rivers during high water season. However, the associated reservoir may promote increased CO₂ emission during the low water season compared to natural emissions from river channels.

Our highest CO₂ fluxes were observed in the IR during the low water season, which is in contrast to previous observations in other tropical and subtropical reservoirs in China and French Guiana (Abril et al. 2005; Wang et al., 2015). In the aforementioned reservoirs lower pCO₂ was observed during the low water season, which was attributed to high photosynthetic rates in the epilimnion. pCO₂ in the XR and other sites outside the reservoirs in the Xingu River also showed lower pCO₂ during the low water season, indicating that higher fluxes may have been mitigated by enhanced primary productivity caused by reduced turbidity. Residence time can also play an important role on pCO₂. For example, the Three Gorges reservoir has a peak in pCO₂ and low Chlorophyll-*a* concentrations during summer and spring seasons when RT is the lowest (Li et al., 2017). In this case the reservoir type (river-type) directly influences water mixing and consequently the RT, similar to the differences observed here between the IR and XR. In low RT reservoirs, nitrogen and phosphorous may not be the limiting factor to phytoplankton growth and it may be restricted by the high flow (Xu et al. 2011). The deficit in CO₂ consumption related to an underperforming phytoplankton community may point to a misbalanced sink in the reservoir carbon balance that remains poorly understood.

CO₂ emissions may be correlated with prior vegetation flooding with higher FCO₂ occurring in areas with the highest carbon stocks such as forests and wetlands (Teodoru et al., 2011). Although vegetation was cleared in the IR before flooding, the upper soil layer may have kept a high concentration of plant-derived material fuelling emissions. This condition explains the higher average pCO₂ in IR compared to XR with the former area also having higher average FCO₂ values. The XR has substrates with relatively reduced carbon storage because almost half of the area represents the original river channel dominated by bedrock or sandy substrates and islands formed by sand and mud deposition, which would not store as much carbon (Sawakuchi et al., 2015).

4.3 Gas transfer velocity (k_{600})

Although no significant difference of k_{600} was observed between the reservoirs of the Belo Monte hydropower complex, the observed gas transfer velocities vary among different environment types. The XR had gas transfer velocities in the range of the Furnas reservoir in the Grande River draining the Cerrado biome (savanna), which has a k_{600} of 19.6 ± 2.5 cm h⁻¹ (Paranaíba et al., 2017). This value is similar to k_{600} values obtained in this study for the XR (23.0 ± 8.0 and 22.9 ± 21.4 cm h⁻¹ during high and low water seasons, respectively). In contrast, the IR had a k_{600} of 7.1 ± 1.5 cm h⁻¹ (high water), which resembles gas transfer velocities of the Lagoa Grande de Curuai (6.0 cm h⁻¹, following Cole and Caraco wind-based model) (Rudorff et al., 2011) in the floodplain of the Amazon River. We observed that in the XR reservoir area, FCO₂ values were higher in the main channel environment. In addition, the relatively stable water flow due to the ROR type reservoir also had a large fetch area for wave formation in comparison with the sheltered flooded areas in bays and small tributaries. This is consistent with the positive correlation observed between wind speed and FCO₂ here and in other large rivers where a vast water surface interacts with wind along its fetch, promoting the formation of waves that enhances water turbulence, k_{600} and FCO₂ (Abril et al., 2005; Paranaíba et al. 2017; Rasera et al., 2013; Raymond and Cole, 2001; Vachon et al., 2013). In addition, at the low water season the elevated gas transfer coefficients

coupled with the short water residence time suggests that the system has a strong influence of water turbulence on k_{600} .

5 Conclusions

In this study, we observed significant variability in CO₂ fluxes related to the type of fluvial environment and land use of areas flooded by the reservoirs of the Belo Monte hydropower complex. The observed CO₂ emissions were 90% higher for the IR compared to XR during low water season indicating that flooded land and higher residence time may play an important role on CO₂ emissions to the atmosphere even in ROR reservoirs. Our measurements comprise the first two years after reservoir filling, which is a critical period to assess GHG emissions from reservoirs. During the high water season, the XR had average CO₂ emissions similar to Amazonian clearwater rivers without impounding and considerably lower emissions than several other tropical reservoirs that have been studied. However, CO₂ emissions during the low water season were higher than natural emissions and the IR CO₂ fluxes exceeded emissions measured in storage reservoirs of other tropical rivers. ROR reservoirs did not appear to alter CO₂ emissions compared to naturally flowing Amazonian clearwater rivers. However, when installed on upland forested areas ROR reservoirs can experience significantly increased CO₂ production rates due to pre-impoundment vegetation and soil organic matter. Despite vegetation removal the IR had the highest CO₂ fluxes observed in this study. Although vegetation removal is considered an effective approach for reducing GHG emissions from hydropower reservoirs we show that tropical reservoirs can still have significant emissions even after vegetation suppression. A long-term monitoring of GHG emissions of Belo Monte working at full capacity and including a more detailed assessment of the downstream sections of the reservoirs is needed to obtain a robust estimate of carbon emissions related to the energy produced by the Belo Monte hydropower complex over its entire lifecycle.

Author contribution

Kleiton R. Araújo collected and analyzed the data and prepared the manuscript with the contribution of all co-authors. Henrique O. Sawakuchi designed the study, cooperated in the field sampling and supported with guidance on data analysis. Dailson J. Bertassoli Jr. also collected the data and conducted the laboratory analysis. André O. Sawakuchi attained the grant award, contributed to setting up the field equipment, measuring infrastructure and designed the field sampling. Kleiton R. Araújo, Karina D. Silva and Thiago V. Bernardi conducted the statistical analysis. Nicholas D. Ward and Tatiana S. Pereira contributed with technical advice and guidance throughout the project implementation and paper writing stages.

Competing interests

We declare that we have no conflict of interests.

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Figure captions

Fig.1: Average river discharge (in $\text{m}^3 \text{s}^{-1}$) of the Xingu River (left Y axis) and precipitation (in mm month^{-1}) (right Y axis) at Altamira from 2004 to 2014. Bars indicate monthly standard deviation. Data is from ANA (2017) and Inmet (2017).

Fig.2: Sampling sites upstream (Irirí river), within and downstream of the reservoirs and the location of the two dams (white bars) in the Xingu river. Black arrows indicate flow direction. Land cover data is based on the vegetation characterization from Almeida et al. (2016), where non-forested area groups pasture, deforested, secondary vegetation, and urban areas.

Fig.3: Boxplots showing the spatial and temporal variability of pCO_2 and FCO_2 . Whiskers indicate standard deviation, boxes are maximum and minimum values and the middle points are mean values. High water FCO_2 (2016 and 2017 campaigns) and pCO_2 from all depths values were averaged to characterize the environmental category. Sampling sites were categorized according to river flow in un-impounded upstream (UU) to sites located upstream reservoirs, Xingu (XR) and Intermediate reservoirs (IR) that grouped sites within reservoirs area, downstream the dams (DD) that corresponded to sites directly receiving turbine outflow and un-impounded downstream (UD) related to sites further downstream with no or low reservoir influence. Temporal variation may be observed by the overall seasonal variation to pCO_2 and FCO_2 during high (A) and low water (B), likewise the spatial distribution to pCO_2 on high (C) and low water (D). Also to FCO_2 (E, F) and k_{600} (G, H) by season are disposed on high and low water, respectively.

Fig.4: Spatial and temporal variation of the FCO_2 values ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) in the reservoirs (XR and IR) of the Belo Monte hydropower complex during high water includes 2 years of data (2016 and 2017) while (A) low water only has one year (2017) (B). Black arrows indicate flow direction; colors and circle sizes indicate the type and intensity of CO_2 fluxes.

Figures

Fig.1

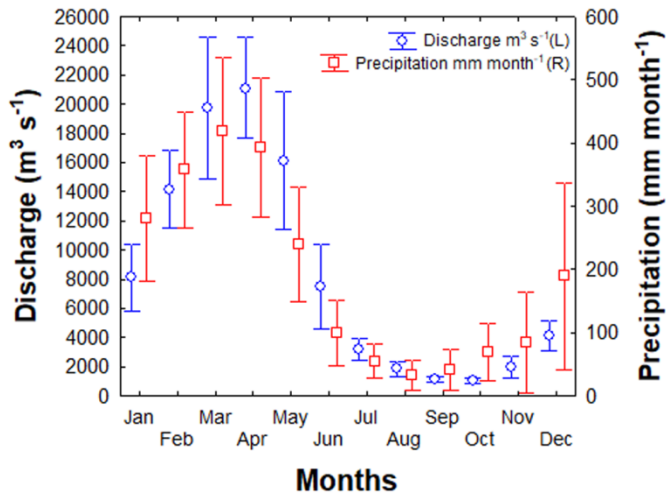


Fig.2

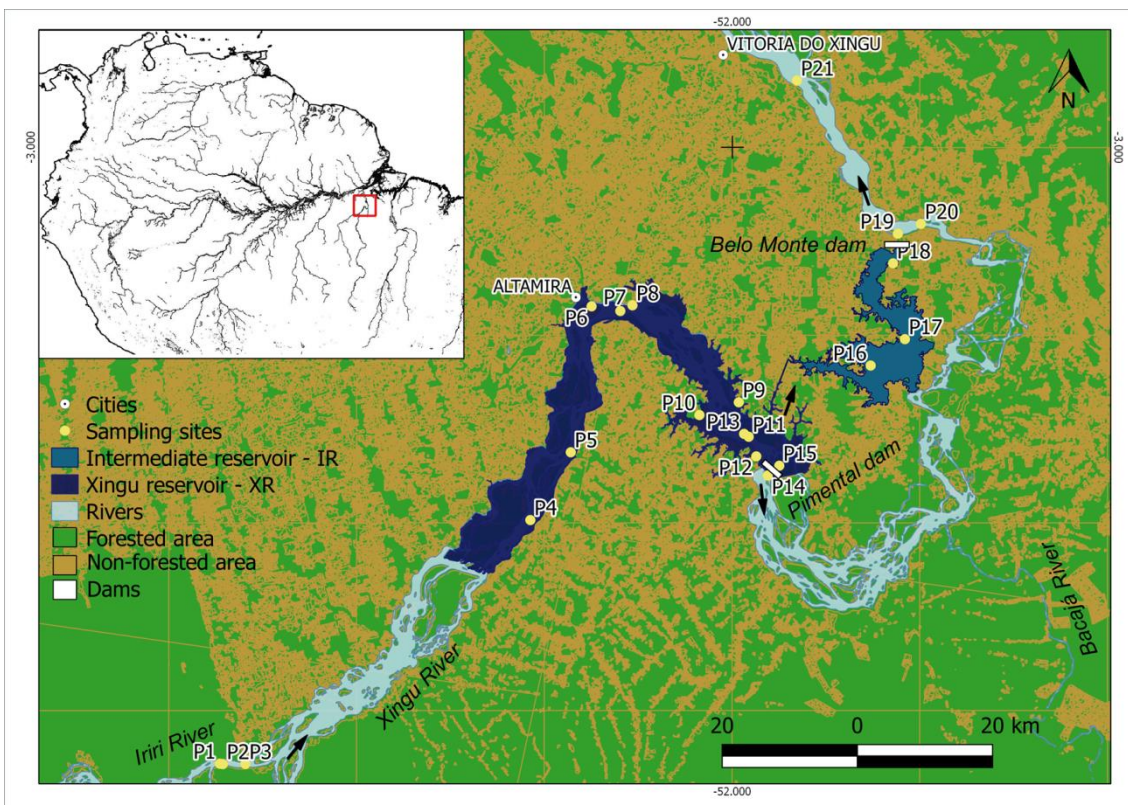


Fig.3

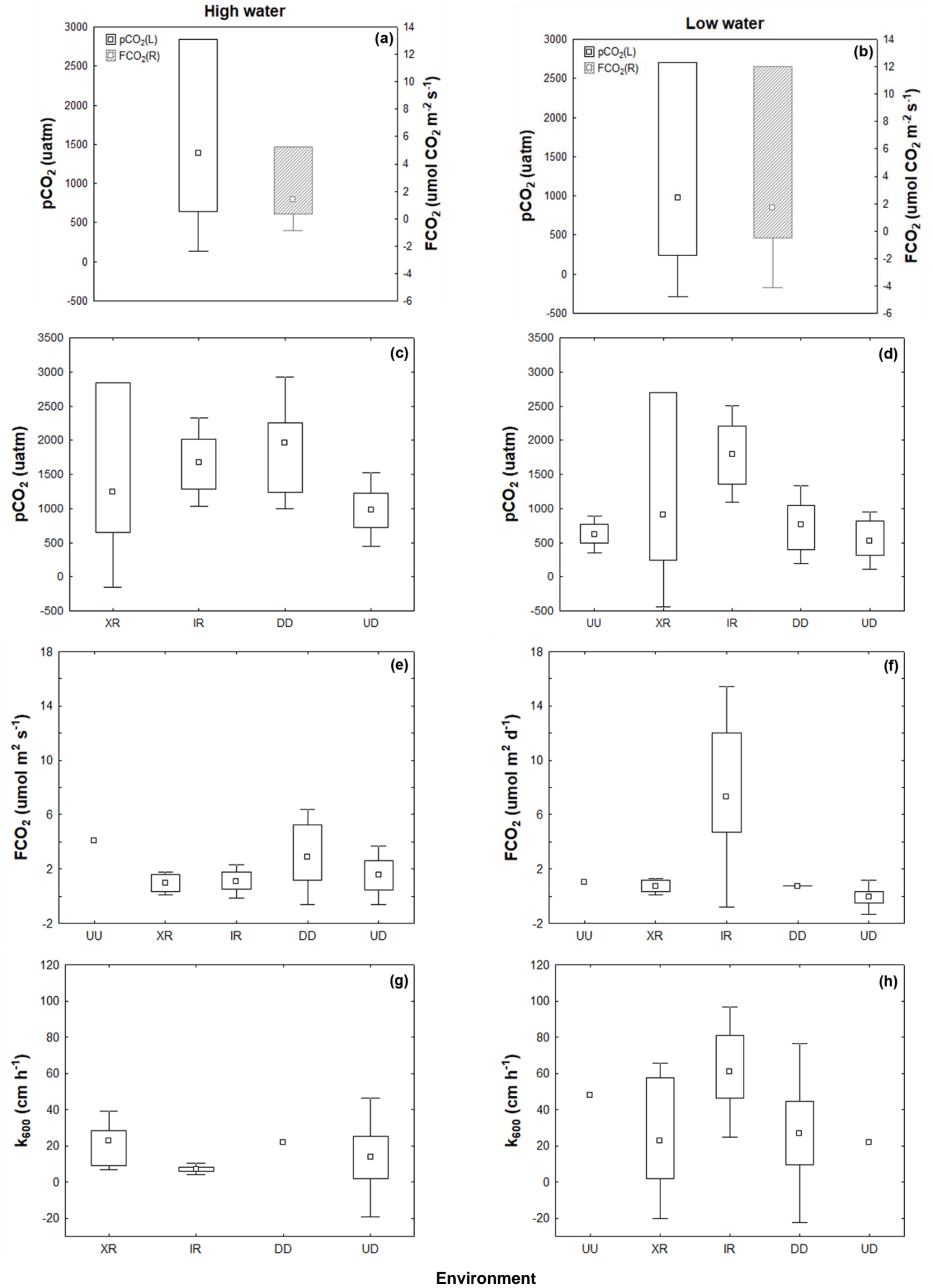


Fig.4

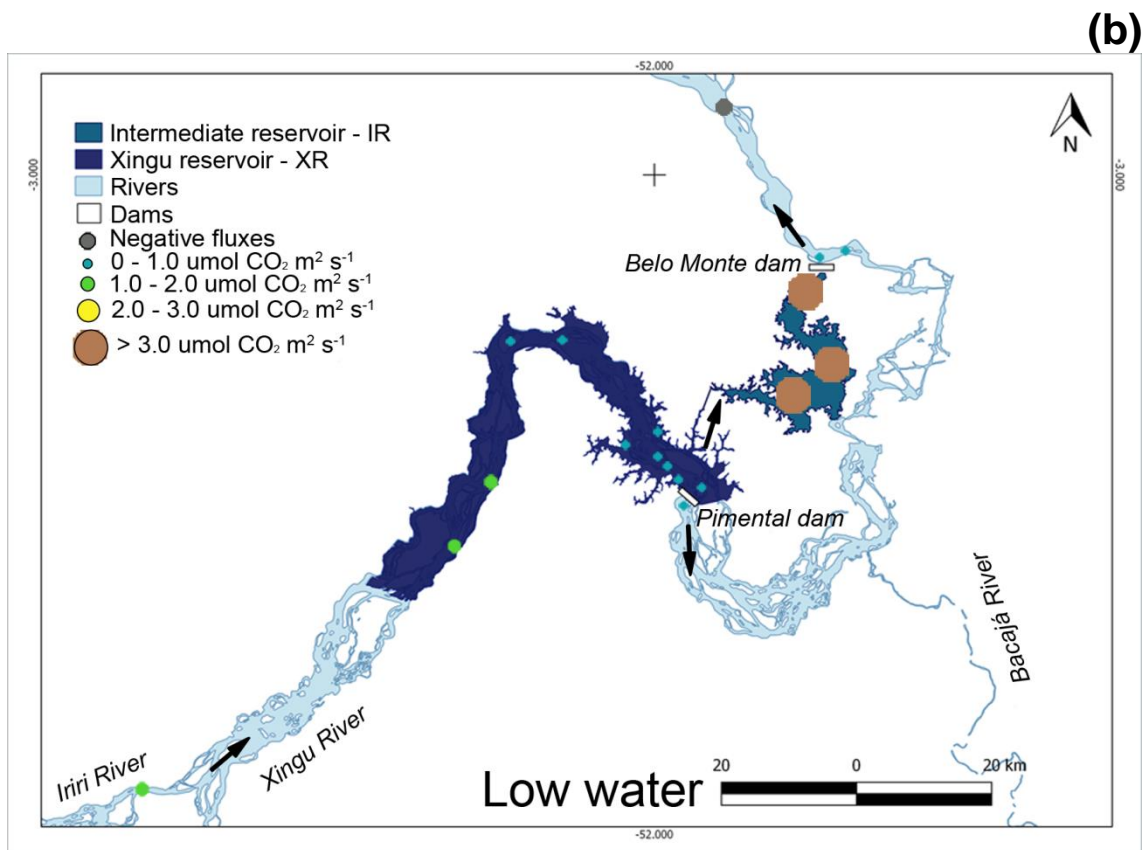
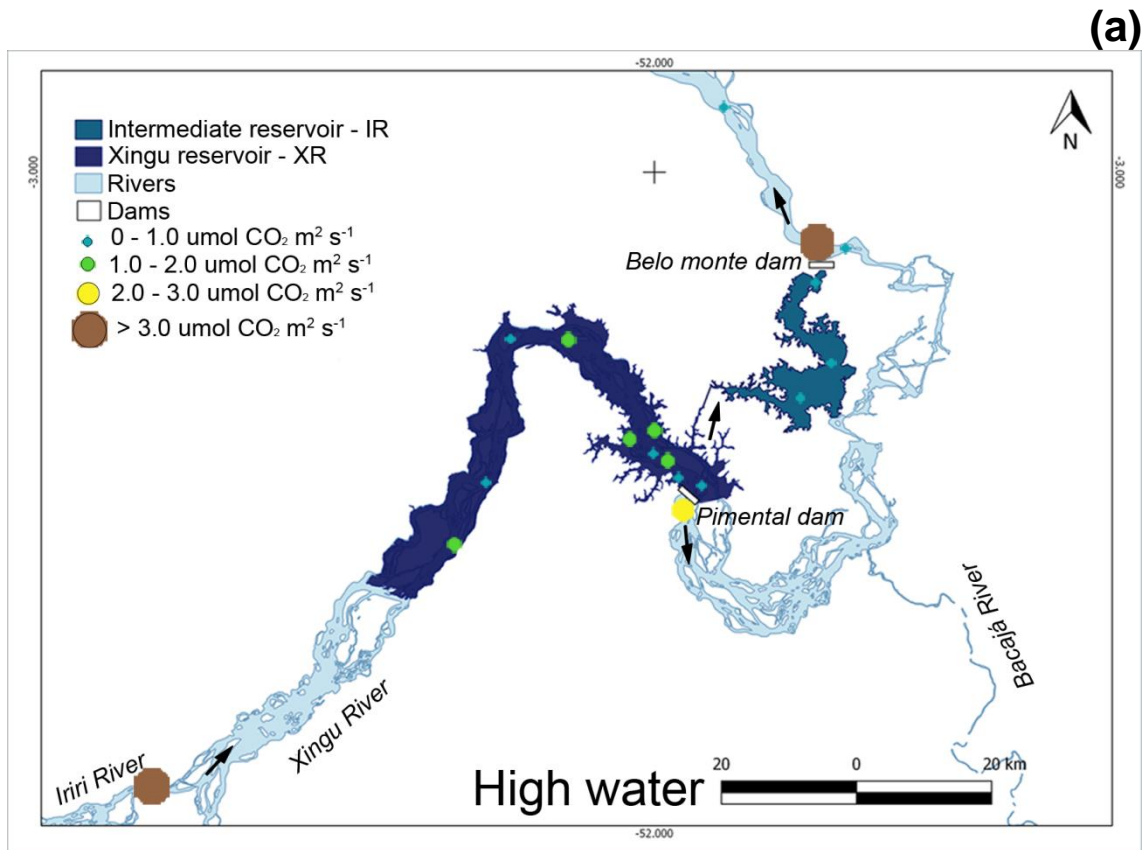


Table captions

Table 1: Locations of sampling sites in the Xingu and Iriri Rivers and reservoirs (XR and IR) of the Belo Monte hydropower complex. Sites were classified according to pre and post-flooded vegetation types, water depth and sampling season (H1: high water of 2016, H2: high water of 2017 and L: low water of 2017).

Table 2: Summary of FCO_2 in $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, pCO_2 in μatm , gas transfer velocities (k_{600}) in cm h^{-1} averages and literature values. High water season averages to FCO_2 comprehends 2016 and 2017 high water seasons since no significant variation was detected. Env = environment, Res = reservoirs, Camp = sampling campaign, Season = sampling season, and n = number of sites averaged to each variable.

Table 3: Statistical analysis results grouped by variable. The pseudo-F (F) and R^2 on analysis column are related to PERMANOVA test and R (Rhô) values are related to Spearman Correlation. Prefix Sur and Bot represents surface and near bottom depths, DO the dissolved oxygen and Temp the water temperature. Temporal, spatial and correlation implications of statistics are described as Effects.

Table 4: Overall physical-chemical characterization comprising the three depth classes (surface, 60% and near the bottom) sampled during the high water seasons of 2016 and 2017, with exception to Temp (water temperature) and WS (wind speed), which corresponds to both high and low water. The variables pH, DO (dissolved oxygen), Cond (conductivity), Temp, and WS (wind speed) are presented according to the environment.

Table 5: Average literature values and standard deviation of FCO_2 , pCO_2 , and k_{600} to Amazonian clearwater rivers according to the season. Referential values were averaged from the Amazonian clear water rivers Tapajós (Alin et al. 2011 and Sawakuchi et al. 2017), Araguaia, Javaés and Teles Pires (Rasera et al. 2013) in the correspondent season when available.

Tables

Table 1

Site	Longitude	Latitude	Pre-flooding environment	Season	Depth (m)
P1	-3.82115	-52.682559	River channel	H1	ND
P2	-3.82168	-52.678553	River channel	L	13.0
P3	-3.82153	-52.678599	River channel	L	8.0
P4	-3.49656	-52.268961	River channel	H2, L	8.1
P5	-3.40623	-52.215154	River channel	H2, L	7.5
P6	-3.21182	-52.187488	Seasonally flooded forested island	H1, H2, L	3.0
P7	-3.21801	-52.149169	River channel	H1, H2, L	20.5
P8	-3.21045	-52.133034	Pasture*	H1, H2, L	0.35
P9	-3.33965	-51.991423	Upland forest*	H1, H2, L	6.1
P10	-3.35664	-52.043752	Tributary, reservoir	H2, L	5.1
P11	-3.38557	-51.978184	River channel	H1, H2, L	19.3
P12	-3.41172	-51.968102	Pasture*	H1, H2, L	6.0
P13	-3.38170	-51.984364	Seasonally flooded* forest	H2, L	7.4
P14	-3.38557	-51.978184	River channel	H1, H2, L	2.5
P15	-3.42413	-51.937447	Seasonally flooded forested island	H1, H2, L	11.0
P16	-3.29069	-51.815787	Upland forest	H2, L	20.4
P17	-3.44253	-51.954685	Upland forest	H2, L	6.2
P18	-3.15452	-51.785845	Upland forest	H2, L	58.3
P19	-3.11501	-51.779624	River channel	H1, H2, L	6.2
P20	-3.10197	-51.748847	River channel	H2, L	2.6
P21	-2.91097	-51.913989	River channel	H1, H2, L	9.0

ND - No data collected.

*vegetation not removed prior to reservoirs filling.

Table 2

Env	Res	Camp	Season	FCO ₂ (μmol CO ₂ m ² s ⁻¹)	n	pCO ₂ (μatm)			n	k ₆₀₀ (cm h ⁻¹)	n			
						Surface	60%	bottom						
Upstream	UR	2016 - 2017	High	4.10 ± 2.16	1	ND	ND	ND	ND	ND	ND			
			Low			501 ±		766 ±						
River channel	XR	2016 - 2017	High	1.27 ± 0.31	6	71.32	ND	138	3	47.94	1			
			Low			771 ±		808 ±						
			High			56.20	ND	205				8	26.58 ± 2.10	3
			Low			612 ±	281 ±	871 ±						
High	0.89 ± 0.33	4	161	143	783	7	24.64	3						
Flooded areas	XR	2016 - 2017	High	0.78 ± 0.38	12	1,674 ±	1,647	2,838 ±	6	8.91 ± 3.22	1			
			Low			17.80	± 333	83.19						
Flooded areas	XR	2016 - 2017	High	0.47 ± 0.12	6	1,330 ±	807 ±	1,498 ±	7	20.49	3			
			Low			1,210	103	203						
Flooded areas	IR	2016 - 2017	High	1.08 ± 0.62	3	1,556 ±	±	1,696 ±	5	7.13 ± 1.59	2			
			Low			375	37.48	455						
			High			1,526 ±		2,069 ±				6	18.02	3
Low	263	ND	152											
Downstream the dams	UR	2016 - 2017	High	2.89 ± 1.74	4	2,122 ±	1,729	2,257 ±	4	21.86 ±	1			
			Low			106	± 689	42.23						
Further downstream	UR	2016 - 2017	High	0.75 ± 0.01	2	663 ±		861 ±	4	26.90 ±	2			
			Low			372	ND	257						
Further downstream	UR	2016 - 2017	High	1.55 ± 1.08	4	969 ±		998 ±	4	13.61 ±	1			
			Low			341	ND	316						
Overall average			High	1.30 ± 1.01	30	1,193 ±	1,618	1,372 ±	27	15.61 ± 8.36	9			
			Low			520	± 525	755						
Overall average			High	1.74 ± 2.94	18	877 ±	676 ±	1,191 ±	31	34.39 ±	13			
			Low			651	276	654						

IR – Intermediate reservoir.

ND - No data available.

UR - unaffected river channel.

XR - Xingu reservoir.

Table 3

Variables	Analysis	p-values	Effect
pCO ₂ by season	F _{1:56} = 9.77, R ² = 0.09	0.0045	Difference among high and low water pCO ₂
pCO ₂ by area	F _{3:56} = 13.36, R ² = 0.37	0.0002	Spatial heterogeneity of pCO ₂
pCO ₂ by reservoir	F _{3:56} = 0.34, R ² = 0.009	0.817	No difference between reservoirs pCO ₂
pCO ₂ by depth	F _{2:56} = 4.06, R ² = 0.07	0.0261	pCO ₂ difference according depth
FCO ₂ by sampling campaign	F _{1:28} = 0.09, R ² = 0.01	0.779	No difference in among 2016 and 2017 high water FCO ₂
FCO ₂ by area on High water	F _{3:28} = 7.94, R ² = 0.43	0.0089	Spatial heterogeneity on FCO ₂ during high water
FCO ₂ by area on low water	F _{3:17} = 2.67, R ² = 0.14	0.08	No spatial heterogeneity on FCO ₂ during the low water
FCO ₂ by reservoir on high water	F _{1:28} = 0.32, R ² = 0.01	0.5811	No difference between reservoirs FCO ₂ during high water
FCO ₂ by reservoir on low water	F _{1:17} = 34.07, R ² = 0.61	0.0003	Difference between reservoirs FCO ₂ during low water
k ₆₀₀ by area on high water	F _{3:9} = 2.42, R ² = 0.70	0.2043	No spatial heterogeneity on k ₆₀₀ during the high water
k ₆₀₀ by area on low water	F _{3:12} = 0.12, R ² = 0.03	0.9441	No spatial heterogeneity on k ₆₀₀ during the low water
k ₆₀₀ by reservoir on high water	F _{1:9} = 0.02, R ² = 0.01	0.918	No difference between reservoirs k ₆₀₀ during high water
k ₆₀₀ by reservoir on low water	F _{1:12} = 5.46, R ² = 0.45	0.09	No difference between reservoirs k ₆₀₀ during low water
Wind velocity by area	F _{3:37} = 6.13, R ² = 0.23	0.0034	Spatial heterogeneity on wind velocity
Wind velocity by reservoir	F _{2:37} = 8.40, R ² = 0.21	0.0016	Difference between reservoirs wind velocity
Sur pCO ₂ x FCO ₂	R: 0.80	0.009	Correlation among surface pCO ₂ and FCO ₂ during high water
Bot pCO ₂ x FCO ₂	R: 0.68	0.042	Correlation among near bottom pCO ₂ and FCO ₂ during high water
Sur pCO ₂ x FCO ₂	R: 0.71	0.012	Correlation among surface pCO ₂ and FCO ₂ during low water
Bot pCO ₂ x FCO ₂	R: 0.45	0.16	No correlation among near bottom pCO ₂ and FCO ₂ during low water
FCO ₂ x Wind velocity on high water	R: 0.37	0.124	No correlation among FCO ₂ and wind velocity during high water
FCO ₂ x Wind velocity on low water	R: 0.72	0.0006	Correlation among FCO ₂ and wind velocity during low water
k ₆₀₀ x Wind velocity on high water	R: 0.73	0.016	Correlation among k ₆₀₀ and wind velocity during high water
k ₆₀₀ x Wind velocity on low water	R: 0.52	0.067	No correlation among k ₆₀₀ and wind velocity during low water
Sur pCO ₂ x Sur pH	R: -0.76	0.009	Negative correlation among pCO ₂ and pH in the surface
Sur pCO ₂ x Bot pH	R: -0.46	0.173	No correlation among surface pCO ₂ and near bottom pH
Sur pCO ₂ x Sur DO	R: -0.93	0.00005	Strong negative correlation among surface pCO ₂ and DO
Sur pCO ₂ x Bot DO	R: -0.86	0.001	Strong negative correlation among surface pCO ₂ and near bottom DO
Sur pCO ₂ x Sur Temp	R: 0.00	1	No correlation among surface pCO ₂ and water temperature
Sur pCO ₂ x Bot Temp	R: -0.27	0.44	No correlation among surface pCO ₂ and near bottom water temperature
Bot pCO ₂ x Sur pH	R: -0.78	0.007	Negative correlation among near bottom pCO ₂ and

			surface pH
Bot pCO ₂ x Bot pH	R: -0.63	0.047	Negative correlation among near bottom pCO ₂ and pH
Bot pCO ₂ x Sur DO	R: -0.83	0.002	Strong negative correlation among near bottom pCO ₂ and surface DO
Bot pCO ₂ x Bot DO	R: -0.86	0.001	Strong negative correlation among near bottom pCO ₂ and DO
Bot pCO ₂ x Sur Temp	R: 0.28	0.43	No correlation among near bottom pCO ₂ and surface water temperature
Bot pCO ₂ x Bot Temp	R: -0.03	0.919	No correlation among near bottom pCO ₂ and water temperature

Table 4

Environment	pH	DO (mg L ⁻¹)	Cond (μS cm ⁻¹)	Temp (°C)	WS (m s ⁻¹)
Downstream of dams	6.62 ± 0.18	5.87 ± 1.39	29.30 ± 4.85	29.52 ± 0.09	1.66 ± 0.88
Flooded areas	6.60 ± 0.26	5.44 ± 2.00	31.60 ± 8.63	29.85 ± 0.66	1.96 ± 1.13
Unaffected river channel	6.75 ± 0.24	7.28 ± 0.73	30.59 ± 6.87	29.72 ± 0.36	2.06 ± 0.84
River channel	6.81 ± 0.21	6.92 ± 0.26	29.86 ± 5.30	29.44 ± 0.62	3.21 ± 0.89

Table 5

FCO ₂ (μmol CO ₂ m ⁻² s ⁻¹)		pCO ₂ (μatm)		k ₆₀₀ (cm h ⁻¹)		Ref
High water	Low water	High water	Low water	High water	Low water	
ND	0.75 ± 0.41	ND	643 ± 172	ND	16.87 ± 10.36	Alin et al. 2011
2.6 ± 1.12	-0.06 ± 0.15	1,646 ± 663	377 ± 154	11.70 ± 5.45	5.175 ± 3.39	
2.3 ± 0.41	0.4 ± 0.18	2,620 ± 810	724 ± 334	8.22 ± 3.80	5.05 ± 0.77	Rasera et al. 2013
1.92 ± 0.96	0.4 ± 0.15	1,799 ± 753	1,037 ± 635	12.20 ± 4.35	7.0 ± 6.64	
1.75	0.76	450	449	ND	16.03	Sawakuchi et al. 2017