Dear editor,

We would like to thank you for the opportunity to submit a revised manuscript.

Please find our answers below after each referee comment *in italic*.

Referee 1 comments

This paper is about the CO_2 concentration and emissions from a newly created hydroelectric reservoir complex in the Amazon area. Given that particularly Amazonian reservoirs have been pointed out as high emitters of greenhouse gases, and since emissions typically are higher the first years after flooding, this study is certainly valuable and interesting. In particular since the new reservoir is a run-of-the-river type, which is supposed to result in lower emissions than storage reservoirs. The study seems to be well-conducted, based on standard methods. However, the presentation severely lacks focus and clarity. I will give in the following a few idea on how the paper can be improved, but I really want to urge the senior authors of this paper to support and help the first author, who is apparently a MSc student and writes his/her first paper (it says in the Acknowledgements). It also takes a thorough revision of English language use and style.

Thank you, we hope to help clarify the role of run-of-the-river dams on CO_2 *emissions, particularly in the Amazon. We have modified the manuscript based on your suggestions, and all authors have carefully reviewed the manuscript for style and clarity.*

What makes this study interesting is that it studies the Belo Monte hydroelectric complex, a all-new installation in the Amazon (it's not even up at full capacity yet), the biggest in the Amazon so far, and one of the biggest in the world, and one that was heavily disputed and criticized. This is not mentioned at all in the paper! I could imagine that the story could be built around the case of this new and huge installation. New reservoirs typically have elevated emissions, but here apparently biomass was removed before flooding, at least partially. Is this visible in the data? One of the reservoirs is run-of-the-river, does it really have lower emission than the storage reservoir? These questions could be formulated as hypotheses, addressed with the data (i.e. figures should illustrate data in a way that relates to these hypotheses), and then explicitly answered in the Discussion. This would give the study a much-needed 'read thread'.

We agree that we did not convey the controversy surrounding the Belo Monte hydropower operations in the original manuscript. We have now added in the Introduction section a brief discussion about the historical debate and controversies regarding the construction of Belo Monte (L63-68). It is worth mentioning that the Belo Monte hydroelectric complex is the largest in power capacity (11,233 MW) in the Amazon, but not the largest regarding the area of the reservoir. Among all the newly constructed or planned dams in the Amazon, Belo Monte is, in fact, the most efficient in terms of energy production per km^2 *of reservoir according to Faria et al 2015.*

Despite complete forest removal, plant-derived material still remained in the Intermediate Reservoir (IR). In the Xingu Reservoir (XR), forest removal was done only *in some large islands. However, 59 % of the area of this reservoir represents the previous river channel where the riverbed consisted of bedrock and sand. Therefore, lower emissions were expected for the XR in comparison with the IR. Nevertheless, our results show higher* CO_2 *fluxes in the IR only during the low water season (Figure 3/Table 2). A possible explanation for the lack of difference in* CO_2 *fluxes among the reservoirs at the high water season could be related to the shorter residence time, vegetation clearing and organic material inputs and availability in this season (more details regarding this can be found in the discussion section (Lines 303-318 and 372-378). A more detailed discussion was added in the lines previously mentioned and percentage of river channel area was corrected (L319).*

The study hypotheses were perhaps unclear in the original manuscript. We have improved this in the revised manuscript, including the addition of the following hypotheses (1) the two Belo Monte reservoirs have contrasting CO_2 *partial pressure (*pCO_2*) in the water and carbon dioxide fluxes to the atmosphere (*FCO_2*); 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 (L95-99). Based on referee 1 suggestions, we have proposed these hypotheses that best fits the manuscript's storyline. Also, some sentences were added to support and better address these hypotheses (L84-91). In order to clarify our objective it was also rewritten (L91-94). Thank you for this useful feedback.*

It will take a thorough rewriting of the manuscript before it may become acceptable, but since it seems to be good data from a understudied site of high interest, I think in the end this could become a valuable addition to Biogeosciences.

Thank you for your comments, they've helped to shape a stronger manuscript. We have worked hard to improve the manuscript quality and hope to contribute to the knowledge of tropical run-of-the-river reservoirs.

Detailed comments: Title: the influence of reservoir traits is not explored to any greater depth. Which traits? I'd suggest to change the title accordingly, maybe "CO_2 concentrations and emission in the newly constructed Belo Monte hydropower complex in the Xingu River, Amazonia".

We intended to use the word "traits" in the title to describe our comparison of storage and run-of-the-river reservoir types. However, we agree that this title was a bit unclear. After a restructuring of the manuscript we decided to accept the suggested title change, which fits the scope of the manuscript well.

L41. The inland water area number seems wrong. See Verpoorter et al. 2014 GRL

The inland water area value number is related only to rivers and streams (i.e., not including lakes and wetlands) based on Raymond et al. 2013. We updated that information with the lake surface area estimated by Downing et al. 2006 and Verpoorter et al.2014. In addition, flux information was corrected and terrestrial carbon influx data was added based on Drake et al. 2018 (L40-44).

L42. Only the Raymond study gives a global estimate, the other citations are regional scale.

The other citations were removed from this sentence to adopt only the global estimate of Raymond et al. 2013 (L42).

L45-54. There's a lot of detail here that is not addressed by this study and could be removed here, e.g. microbial community structure or priming.

The goal of this paragraph was to address the factors involved in CO_2 *production. We agree that this section was perhaps too detailed. However, we feel that these concepts link well with our discussion of OM availability later in the manuscript (Lines 312-318 and* 380-382*) as* CO_2 *sources. Thus, we have altered these sentences to improve flow with the rest of the introduction, but feel that these are important concepts to introduce (L45-57).*

L70. While emissions are typically high, the lifetime emission of a reservoir is probablyrather a function of the long-term emission level, and the short initial emission pulse
may have less influence.

We have modified this sentence to point out that emissions during the initial years are typically highest and the most uncertain, but that sustained long-term emission rates are likely important for the overall carbon balance of the system over its lifetime (L73-83).

Study Area: This must mention that the installation is new, and it must describe in how far and where vegetation was removed before flooding, and when the flooding took place.

Thank you, we have made this change (L119). In addition several other alterations had to be done in this sub-section according to the new hypotheses. Reservoir description was refined and rewritten as retention time calculations (L119-143).

L106 and 114. The water retention times are very short, even for the storage reservoir it's only 1.5 days. Are these numbers correct? If so, these reservoirs, given their size, must be characterized by quite strong water flow, and thus the gas exchange velocity is probably hardly related to wind speed, but rather to water speed.

Our residence time (RT) calculations had a mistake that is now fixed. The corrected RT was 20.2 and 3.4 days for IR and XR, respectively. Details regarding the RT estimate and values can be found in the manuscript (L135-143).

L112. 97% of the capacity are at the Belo Monte dam, so the ROR dam only produces 3% of the energy even though it contains one third of the number of turbines?

The difference among both dams is not only in size and turbine number. The turbine model also differs between dams, which influences the generating power. The main powerhouse is equipped with 18 turbines Francis type with active unit power of 611.11 MW as complementary powerhouse has 6 Bulb type turbines that are considerably less potent with active unit power of only 38.85 MW.

L116. Where is the hypolimnion typically starting? Did you do any depth profiles of T and/or DO? If so, please show and report! If not, please cite a study that states that the thermocline is typically at >20 m.

During our samplings, the water column had a well-mixed pattern without variation in DO in most of the reservoir's area. The hypolimnion was only apparent in the IR, close to the dam, where DO decreased drastically at approximately 50 m from a total depth of 58 m. However, as observed on Faria et al (2015), its formation is not expected on Belo Monte Reservoirs. Therefore this sentence was altered, and hypolimnion information was withdrawn. We have now included depth profiles in material and methods and graphs of variables such as DO, temperature, etc. in the supplemental material (L207) (supplement material figure S1).

Section 2.2. It would be more easy to understand if you first described your sampling campaigns, and then tell about any gaps.

We have made this change accordingly (L187-189).

L144. Why was 60% of water depth chosen? Seems arbitrary. Also, it would be good to know the actual depth at these sites. A raw data table should be submitted alongside with the paper.

60% depth was chosen as a mid-depth sampling point to compare surface and bottom waters. In deeper sites, the three depths (surface, 60%, and near-bottom) were sampled due to the variation in water velocity. Our goal was to sample depths with different organic and inorganic matter abundance due to water flow transport (L162-164). We have added depth information to Table 1.

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

We are confident in our 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 not added these details to the manuscript, as transferring gas to vials is a common method.

L154. Start this paragraph with saying "Diffusive CO_2 emission was measured with floating chambers". Also, please give the dimensions, shape and type (transparent / opaque) of the chamber.

The text was changed accordingly (L173).

Two types of floating chambers were used in different sampling campaigns. Both types were made of opaque polypropylene and were covered with reflective aluminum tape. They were round and their volume and area were the 7.7 L and 0.08 m^2*; and 6 L and 0.07* m^2*. Information about the chambers used was added to the text (L174-175 and L178-179).*

L161. I guess you mean logging frequency, not time.

Exactly, we have modified this (L181).

L168. Atmospheric pCO_2 of 380 ppm seems like an outdated value, or are these your own measurements in air?

The atmospheric pCO_2 *of 380 ppm was used based on an outdated database. The data was re-evaluated and now measurements were discarded when the* R^2 *of the linear relation between* pCO_2 *and time* ($\delta pCO_2/\delta t$)*, measured during chamber deployment, were lower than 0.90* ($R^2 < 0.90$) *or in cases where we measured negative* FCO_2 *when the surface water* pCO_2 *was higher than the atmospheric* pCO_2 *based on measurement done at the same site. However, this happened only two times and could be attributed to some source of* CO_2 *contamination when placing the chamber into the water — thus, starting with a higher* pCO_2 *than the water (L187-189).*

L184. This sentence seems unnecessary

We have removed it.

L191. A station is stationary. You probably mean a handheld meter or device?

Updated as suggested (L213).

2.5. Statistics. I did not know Permanova, so this should be better explained. Is it a parametric method? Because it is stated that the data did not follow normal distribution. However, later in this paragraph, you mention some data were normally distributed and used t-test; this is confusing. Also, in the entire paper, report the actual p values, not just if p is lower of higher than 0.05.

Agreed, the method was superficially mentioned in the manuscript. PERMANOVA is a multivariate variance analysis to compare variability between and within groups using permutation to obtain p-value. Due to the different hypotheses tested, the data set had to be adjusted and consequently altered the data distribution. In the case of T-Test, sites located on "outside reservoirs" and "downstream of the dams" were not considered and also season. Related to p value, we have now reported all the p-values accordingly to the real value obtained from the statistical test. PERMANOVA analysis was better detailed in the methods section as suggested (L219-221). We have removed T-Test analysis since it is related to a descriptive result.

Results. In general, this section describes many findings and patterns, but it does so in a quite unstructured way, and is therefore difficult to follow. I really think it would help this paper if only the results were presented that are relevant to the hypotheses or research questions. Also, the language describing the patterns should be improved. For example, it needs to explained what numbers are given (e.g. L208, is this the mean ± standard deviation, or something else?), and comparisons between two groups describe a difference and not a variation (L208). Also, increase and decrease (e.g. L245 and L249) refer to a change over time and thus some form of time series data, while this study has data for two discrete sampling occasions, and thus can only speak about differences. It should also always be very clear what exactly was compared. For example, in L213, it was unclear what was tested here, the variability in pCO_2 within and environment, or between environments?

Thank you, your comments were very constructiveto this section. Throughout the whole text, we presented values as mean ± standard deviation and indeed we were using the term "variation" when we meant "difference". It was corrected.

Most of this section was re-written for a clearer understanding (Lines 230-246, 254-259, 261-272 and 274-278). Here we meant that we have tested the pCO_2 variability between environments.

Several sentences had to be moved or removed from the text resulting in a complete rewriting of the section. The over usage of average values was revaluated and most of them also removed. Statistical analyses previously presented only for surface water are now were updated to include all depths (L241-243) (Table 3).

Again concerning statistics, it is unclear to me how a comparison between two groups can render a R^2 value, but maybe that's a part of the PERMANOVA, and should in that case be better explained in the Methods.

Our statistics description did not detail PERMANOVA correctly in the previous version of the manuscript, as so this test became unclear to the reader. PERMANOVA analysis tests similarity using a Euclidian distance index through permutations. The R^2 value is generated by permutations. As mentioned above, PERMANOVA analysis was better explained in the methods section as suggested (L219-221).

L215. Here you speak about spatial variability, but do you mean differences of means between different environemnts, or the variability of measurements within one environment type?

Here the test is to evaluate if the different environments (reservoirs, downstream the dam and outside the reservoir) presented different fluxes in each season. Temporal trends sometimes may mask some spatial patterns that only become visible when seasons are treated separately. Therefore, here we refer to a PERMANOVA test similar comparing pCO_2 between environments.

L219. “Outside reservoir areas” is not a very illuminating term. Could choose another name?

We agreed and replaced it to “unaffected river channel” (L149).

L224. 281 µatm at 60% depth, how much is that in meters? And how can deep water be undersaturated in oxygen? Typically it is oversaturated. Or was this above a macrophyte bed?

The total depth of this site is 7.5 m (Table 1), and the sampling depth was 4 m. This sentence describes pCO_2, not dissolved oxygen. The value of pCO_2 equal to 281 µatm was observed in the undisturbed river channel without macrophyte bed. Sub-atmospheric pCO_2 has been previsouly observed in other large clear water rivers in the Amazon region, resulting in negative CO_2 fluxes (Rasera et al. 2013), indicating net primary production. We are not sure what you mean by the question of how deep water can be undersaturated in oxygen—these large clear water rivers in the Amazon are known to have low turbidity, favoring algal productivity and resulting in high dissolved oxygen levels. However, in the Amazon mainstem where the high turbidity reduce algal productivity lower levels of dissolved O_2 and high pCO_2 are observed due to net heterotrophy.

L231. Here it says the data from the two seasons were pooled, but L237-241, the seasonal data are discussed separately. This is confusing.

Thank you for this comment. Our FCO_2 data is related to a time period of two years, including three seasons (2016 high water, 2017 high water and 2017 low water)(L189-191). The data pooled are from the same season, both high water, sampled with the same equipment and they were not statistically similar(L244-246). High and low water were measured with different equipment due technical issues and treated separately (Lines 174 and 178).

L246. The seasonal difference in IR was very small, certainly not a "pronounced difference". Interestingly, FCO_2 was very different between seasons in spite of similar pCO_2, which indicates a strong variability in k. Was this the case?

Despite the difference in averages, we observed that the seasonal difference in the IR was not significant and we removed it from the text. Regarding k, no statistically significant variation was observed between seasons (L274-276).

L250. What kind of spatial analyses? Comparison of the means for different environments?

PERMANOVA was used to compare simultaneously the variation of FCO_2, pCO_2 and k_{600} between both reservoirs. This analysis did not generate difference of means, but the dissimilarity within versus and between groups through distance measures.

L251. "evaluated together", is this warranted? Were these two groups similar?

Our results indicate that they are similar. We have checked it by changing the river channel category to unaffected river channel (wich was grouped with outside reservoir sites, downstream the dams included). Only flooded areas represented each reservoir emission. Nevertheless, the same results were reached. A different classification reveals overlapping patterns; if a significant result was reached it would point to dissimilarity among groups.

L256. "Pasture" is a new and undefined category.

Upland forest and pasture were the main land cover in the areas flooded by the reservoirs as described in the description of the study area and measured sites (Table 1). They are both included in the flooded area category for the previous analysis. Here we evaluate if there was a difference in pCO_2 and CO_2 flux among the type of vegetation flooded. Thus, they were considered as a flooded area subgroup.

L262. What's the measure of variability? It seems that in this study, you mostly compared means, but if you want to address the variability, you maybe want to look at relative standard deviations, interquartile ranges or something similar. If you want to stick to comparing means between environments, please formulate this explicitly in the text.

There was some confusion with the term from our part. Our analysis describes difference by a distance matrix that calculates the similarity within and between groups, not variation. We assume that the poor statistics section may have complicated much of the reading. We have rewritten that section and replaced "variation" by "difference" in the whole manuscript.

L263. Varied significantly between what?

The FCO_2 differed significantly between XR and IR reservoirs during the low water season. This sentence has been modified accordingly in the revised manuscript (L268-269).

L266. The 90 km downstream site is so far away it's not even on the map. I wonder in how far it is relevant to this study at all, or could safely be omitted.

Thank you for the observation. That was a mistake in the writing; the 90 km site is downstream of the Pimental dam (P20 site – Fig. 2), not Belo Monte. We believe that this site is relevant because of its location downstream of the Volta Grande do Xingu (Xingu Great Bend) region and a few kilometers upstream to where the Belo Monte dam discharge back into the original river. This information was properly corrected (L257-259).

L270-273. Go straight to the results instead of first describing what was not done.

We have made this change (L274).

L275. The relationship between k_{600} and wind speed is very weak. At any wind speed, k can vary with a factor of 2-4. This is quite often the case, and maybe even expected in such system where water moves fast, and thus water turbulence is quite independent of wind speed.

Thank you for this comment. We agree, particularly considering the short residence time of the Belo Monte system. Since there was no significant k variability, the water turbulence may be the major factor driving CO_2 diffusion. We have corrected it in the manuscript (L276-277).

All in all, the Results give many comparisons, What about making matrix tables where you can give test statistics for each comparison?

Thank you that was a great suggestion. We have added such a table (Table 3).

3.3. Did you ever measure depth profiles? Would be very interesting to show these data, to asses if really the turbine intake is in the epilimnion, and to assess the potential outgassing through turbine passage.

Yes, depth profiles were made for temperature, pH, O_2 and conductivity. CO_2 was measured at the bottom, 60% of site depth and at the surface (0.3 m) during high water campaigns. Our data show a well-mixed water column without stratification close to the Pimental dam in the Xingu Reservoir (suplemmentary material figure S1). In addition to surface, correlation results of near-bottom depth were added (L292-294) (table 3).

Nevertheless, its intake is at the bottom, where even with high O_2, the pCO_2 is higher than at the surface. In Belo Monte dam pCO_2 follows the same pattern, although the O_2 decrease drastically at approximately 50 m (as mentioned above). As such, Belo Monte intake is in the O_2 rich zone. The depth profiles can be seen in the supplementary material, Figure S1 .

L292. This is not one of your results.

Removed.

L296. The Discussion should start with your most important finding, not with citing other studies.

Updated as suggested (L297-309).

L303. This seems to be an important finding. Could you make a figure that illustrates this finding, to make it visible and convincing?

Thank you for the suggestion. The Figure 3 was updated , and this findings has been highlighted in panels (e) and (f).

L309-326. This discussion is very hypothetical and not much related to your data.

Thank you for this comment. We have deleted this paragraph.

L327. Not really. In your own data, there is an example of differences in k producting very different emission fluxes in spite of similar pCO_2 (see my comment above).

We have added the clarifying statement "…although we did observe some specific examples of differences in k producing different emission fluxes even when pCO_2 *was similar" (L297-298).*

L328-334. This may be the main message of this paper. It would be good if you produced a Figure that illustrates this finding.

We have made a table summarizing these results (Table 5).

L340-341. The Methods need to describe explicitly which areas were flooded with intact biomass, or after biomass harvesting.

This information was already presented in table 1, however it was not as explicit as it could be. More information about the vegetation removal in each reservoir was included in the text (L125-129).

L350. Could you actually observe increased water clarity in your data / samplings? If not, this discussion is not helpful to explain your data.

No. Our turbidity data was not reliable due to poor calibration, therefore, we removed it from the paper. We have removed this sentence.

L355. pCO_2 were only lower during low water compared to high water in the downstream and dam categories. For flooded and river channel, they were similar (Fig.3). So it is not warranted to speak about a "drastic decrease".

We have deleted the word "drastic" from the text. The statistical test showed difference among seasons and to environment categories, which is corroborated by the lower pCO_2 *averages during low water both to flooded areas and river channel (as shown in table 2). This sentence was rewritten in the new version of the manuscript (L326-329).*

L375-383. Could the difference between Belo Monte and Petit Saut be explained by different water intake depths? Do you have water profile data?

After further observation, the near bottom anoxia in IR could be related to contamination (probe in contact with sediment). The most reasonable assumption is that any site had a stratified pattern (Supplementary material Figure S1). As Petit Saut has hypolimnetic water intake and lack of vegetation clearing the downstream emission is higher than Belo Monte, a ROR complex with well mixed waters and vegetal cover removed in most of the flooded areas. This information was updated in the manuscript (L346-353).

L391. It seems not warranted to assume that any site or time point should serve as a "reference" for river pCO_2, since it varies in time and space.

We have deleted this sentence.

L395. What is meant by "turbine activity"?

Since it was a cloudy discussion it was deleted.

L398-406. I think you could further explore the patterns in k, e.g. between environments, and between reservoirs. Were the values in these reservoirs rather similar to other reservoirs or lakes, or rather to rivers?

The k_{600} *in the XR (22.99 ± 8.00 and 22.89 ± 21.40 cm* h^{-1} *on high and low water, respectively) were in the same range of the Furnas reservoir (19.58 ± 2.5 cm* h^{-1}*) installed on Grande River located in Cerrado region (Paranaíba et al., 2018). The IR presented a wider range of values among seasons (7.13 ± 1.59 and 60.80 ± 18.02 cm* h^{-1} *on high and low water, respectively), but the* k_{600} *observed at the high water season was similar to values observed in the Javaes River (8.22 ± 3.80 cm* h^{-1}*) (Rasera et al 2013) (L388-393).*

L403. There is no strong positive correlation between wind speed and FCO_2 in your data. Fig 5 shows weak relationships, at best.

Thank you for the highlight, we have updated the text as suggested (L393-401).

L423-425. This sounds like the main result of this study. Make a figure to show and highlight this result, and discuss it in terms of reservoir properties and operation type.

We have included a new figure that shows this difference, and the suggested points were included in the discussion (Figure 3).

Figure 3. In panels c and d, I would suggest you order the environments in flow direction. That is, upstream first then XR environments, then IR environemnts, then downstream. If it gets too crowded, make two separate panels for high and low water. And the same for pCO_2 and FCO_2 and k_{600}, i.e. you may end up in 6 panels instead of 2. Together with panels a and b, it would be 8 panels.

We have reordered and changed the categories. We added the categories in the following order: "unaffected river upstream", "XR", "IR", "downstream of the dams" and "unaffected river downstream". Panels were also separated by season and new panels k_{600} *were added.*

Figure 4. When seeing this figure, I wonder how much of this spatial variability is driven by differences in pCO_2, and how much by differences in k.

To make the spatial variability more visible, we have added one more panel related to k_{600} *to figure 3.*

Table 2. What are the values, mean ± standard deviation? How many measurements are behind each of these averages? Could you introduce a column with "n"? The k values are high and resemble rather riverine systems than lakes or reservoirs, I guess an effect of the fast water flow. The comparison with literature values would be better and more visible in a graph than in a table.

The values are averages ± standard deviation, except for Sawakuchi et al. 2017. During high water FCO_2 *was measured three times (L177), and during low water two* FCO_2 *measurements were made simultaneously (L180) and headspace was sampled on triplicates (L164). It is feasible that the turbulence in both reservoirs is mostly related to water flow. A compilation of the literature information of* k_{600} *were made and is presented in Table 5.*

Referee 2 comments

Please find our answers bellow after each referee comment in *italic* font.

Review of Araujo et al. This manuscript describes the results from a 2-yr study during high and low water seasons on the Belo Monte hydropower complex that consists of two main reservoirs, one of which is defined as a run-of-river and the other as storage. The authors aimed to contrast the impact of these two reservoir types on the CO_2 dynamics of the entire complex. Additionally, they contrasted CO_2 dynamics across various flooded environments within the complex. The manuscript has some nice data but is predominantly descriptive. Regardless, data in tropical reservoirs is currently necessary and it is interesting to contrast these two types of system. Not to mention the huge dispute over this massive Amazonian project. I have many suggestions for how to improve this manuscript before this paper is ready for publication.

We appreciate your suggestions, which have greatly enhanced the manuscript and its potential impact.

General comments

1. Be careful with the word 'traits' in the title. It implies features that do not vary in time. Is that the focus here? Do you mean ROR vs storage, plus flooded landscapes? That would be okay then. But if that was the case then I did not get the impression enough from your discussion that that was your focus. You need to bring out your main points much more. Try focusing the research questions or objectives more narrowly. This will help you throughout the entire publication.

Thank you and that was the point. Our initial goal was to define the group of characteristics that classify each reservoir as 'ROR' or 'storage'. However, after restructuring the hypothesis and re-evaluating the reservoir's characteristics we removed those classifications. Although a larger flooded area, deeper and a lake like aspect the Intermediate reservoir, it could not be classified as a storage reservoir due to its short water residence time (L142) (Faria et al., 2015). Both reservoirs were considered as ROR (L87) and they were now compared according to their extention of flooded area and water residence time (L84-91). Consequently , we have changed the tittle accordingly to the Referee 1 suggestion ("CO_2 *concentrations and emission in the newly constructed Belo Monte hydropower complex in the Xingu River, Amazonia").*

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

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

3. Abstract needs more quantitative results in it

Thank you, this section was revised. Some unnecessary information was removed (L2-9) to make space adding a better description of our results findings (L9-24).

4. Introduction does not discuss the importance of this particular reservoir more.

More details concerning Belo Monte and its controversy were added to the text as suggested by both reviewers (L63-72).

5. Methods – description of how reservoirs are connected is not clear. In the map figure there appears to be a channel connecting them too. Please improve the description of how the reservoirs interact, including flow directions, which should be on your Figure 2, and individual surface areas.

The Pimental dam in the XR, regulates the water flow towards the IR through a 28 km artificial channel, constructed at the left margin of the XR, to feed the IR where the main powerhouse is located (Brasil, 2009) (L122). The channel description and reservoir interaction were clarified (L119-124). Also, Figure 2 was updated as suggested.

6. I find section 3.1 of the results very confusing to read and absorb fully. There are a lot of numbers that are perhaps not necessary and very distracting from understanding what you are trying to describe. I would suggest a schematic to help describe the temporal (high vs low water) variability you see that also includes the spatial variability (across environments). You can use weighted markers for the various fluxes and concentrations that correspond to high and low values, if not the real values.

This section was revised for conciseness and clarity. After these changes the text became clearer and we believe that a schematic figure is not needed.

7. Figure 2 – needs arrows for direction of flow.

Done.

8. Figure 3 – You can make these 4 plots into just 2 in the following manner: put the white boxplots from (a) and (b) that are pCO_2 in the beginning of (c) labeled ‘High water’ and ‘Low water’, and the gray boxplots that are for FCO_2 in the beginning of (d) with the same labels. Also, are the environments in c and d labeled in the proper order – from one are to another? Or does it not work like that because of the reservoir geomorphology? Either way, I would put downstream the dams on the right side since most people read left to right and you naturally think downstream to the right.

Thank you for the interesting suggestion. The environments were previously organized in alphabetical order on the plots. However, we agree that it will be easier for the reader to follow the downstream orientation. Therefore, it was corrected to flow order. We added more plots to this image according to referee 1 suggestion, with season separately and an additional variable (k_{600}). The categories were also changed to “unaffected river upstream”, “XR”, “IR”, “downstream the dams” and “unaffected river downstream”. In the last version there was an error in the FCO_2 unity. Fluxes were in µmol CO_2 m^2 s^{-1}, but instead s^{-1} in the legend was written d^{-1}. This error was corrected.

9. Figure 4 – you need units listed for the values; direction of flow arrows would be good; and mention in caption that (a) includes 2 years of data while (b) only has one year (and list which years).

Updated as suggested. Figure 4 had the error on s^{-1} unity replaced by d^{-1}, that was already corrected. Also colors were updated.

10. Figure 5 – you mention these figures in terms of stats but there are no lines on it and no equations or states in the figure caption.

These figures show the correlation between k_{600} and FCO_2 with wind speed, We have used the Spearman correlation test, which is ranked test, and do not have mathematical model or equation. The Rho values were reported for each comparison. In this new version, figure 3 includes the k_{600} results, as suggested by referee 1 and the figure 5 is now included in the supplement material.

11. The discussion seems like a bunch of descriptive paragraphs thrown together. It is lacking some cohesive red line to follow and it is hard to locate your main points. Perhaps you can start to fix this by using subsections. Looks like you broke it down into the following: Seasonal variability; Vertical heterogeneity; FCO_2; Spatial variability;

Comparison to other reservoirs; k600; Operation. These are all just descriptions of data in reality. You want to discuss the most interesting findings of your study and then compare them with other studies. Figure out your few most important findings and try to arrange the discussion around those first. You also measured the system right after flooding, which is when emissions should be highest. This needs to be addressed in your conclusions.

The discussion was rewritten in order to address the main points of the work (L297-401). The text was rearranged and divided into subsections that we believe are now more connected with our main findings and hypothesis, as nicely suggested. The high water season reservoirs comparison was removed since they were not significantly different. We have also highlighted in the manuscript that measurements were made during the first years after impounding (L406-408).

Specific comments

Line 16-17 – did you measure clearwater rivers yourself ? if not, then either change or delete this sentence because it makes it sound like you.

Our measurements were done only on the Xingu River; therefore, we altered the sentence to clarify this issue (Lines14 and 17).

Line 41 – You mention that ‘inland waters’ have an area of ‘624,000 km2’ and cite who with regards to this number? This number is very small compared to the 2.5 – 5 million km2 range that actually exists for all inland waters surface area coverage. I think you mean to cite only rivers surface area with your 0.624 million km2 value so you need to be specific when you say ‘inland waters’ and you need a specific reference for this river surface area number. But then you cite the 1.8 – 3.8 Pg values, presumably from Drake et al. 2018 and those values are for all inland waters specifically. If you want to discuss inland waters surface area coverage total then you need to use either Downing et al. 2006, Verpoorter et al. 2014 or Messager et al. 2016 or Feng et al. 2016.

The area previously mentioned was for rivers and streams according to Raymond et al. (2013). We have changed this paragraph to discuss inland waters as a whole and on a global scale (L40- 44).

Line 45 – clean up language (e.g., don’t need ‘water’ so many times

Done (L45-46).

Line 50 – should be: ‘to the autochthonous respiration of OM deposited’

Thank you, we have updated this sentence as suggested (L50).

Line 54 – should explain more how the stimulation of OM decomposition via those two processes actually effects CO_2 – similar to how you did in the first half of the sentence saying higher CO_2 uptake

Agreed, we have divided this sentence in two and rewritten it to clarify the text. Those processes were added to the text and briefly explained as suggested (L52-56).

Line 66 – I believe it was actually DelSontro et al. 2010 and not 2016

Absolutely, thank you. This citation was corrected (L77).

Line 69-70 – Start a new sentence with ‘Newly flooded reservoirs...’ and then give examples/references of the few poorly studied reservoirs.

We have rewritten and added more information about GHG emissions from newly built and future tropical reservoirs estimates from the literature (L73-83).

Line 73 – should be ‘variability’ and not ‘variation

Updated as suggested (L93).

Line 73 – give the abbreviation for fluxes here ‘(FCO_2)’ that you will use the rest of the paper, and delete ‘and its relevance for GHG fluxes’

Thank you, corrected accordingly (L93).

Line 75 – end this sentence with ‘..complex in eastern Amazon, a tropical region poised to gain XXX more hydropower projects in the coming decades (REF).’ This puts your work into a bigger perspective at the end of your intro.

Thank you, this fragment was included, but converted in another sentence (L94-95).

Line 83 – the 1984 study is quite old… Is there nothing newer?

It is related to a classical study that classifies Amazonian rivers according to physicochemical characteristics. Although relatively old, it is still largely used for the classification of large Amazonian river.

Line 98-100 – in this sentence give the names of the two reservoirs after you mention them.

This sentence has been removed, but new information about the reservoirs and the Belo Monte complex were added in the introduction, including reservoir’s names (Lines 84 and 85-86).

Line 101 – give more details about these calculates from Faria et al. 2015

The residence time was calculated by the equation RT= V/ Q, where RT is the residence time in seconds, V is the reservoir volume in m^3 and Q is the volumetric discharge in m^3/s. To convert RT in days the value was divided by the number of seconds in a day. We altered this sentence and added this information in the text (L135-143).

Line 104 – once you have given the XR abbreviation for Xingu Reservoir then use it for the rest of the paper, and do you mean ‘as islands’ instead of ‘in islands’?

This sentence was removed.

Line 107 – ‘classified’ instead of ‘denominated’ – and this paragraph should contain the surface area of these reservoirs already

This sentence was removed. Reservoir areas were added to the text on lines 125 and 128.

Line 115 – the residence time of the IR reservoir is still ridiculously short (1.57 days). How do you call that a storage reservoir? Still want to know the surface area of these reservoirs already

There was an error in our RT calculations due to the discharge data used. The previous RT values were based on an environmental impact study (EIA) that estimated the highest discharge values of each reservoir. We performed new calculations using the average historic discharge series from Water Agency of Brazil database. The corrected RT of 20.2 (IR) and 3.4 days (XR) were updated in the manuscript. In addition, we added the surface areas of the IR (154 km²) and XR (342 km², including the 228 km² originally occupied by the river channel). Due to the low RT of the IR we are not considering it as a storage reservoir. However, both reservoirs are still compared (*L125-134*).

Line 116 – should give maximum depths of the reservoirs

Thank you. Maximum depths were added (L120).

Line 117 – why did you give the total surface area of the 2 reservoirs together? You should provide values for the two different reservoirs. If this is difficult because of the difference between rainy and dry season then state this but still give approximate values for the individual reservoirs since you are evaluating them separately.

The reservoirs areas were added as mentioned above.

Line 121 – what is the 25.4 km2/MW? Why should I care about this value? Give some explanation behind your reporting of this value (or don't report it).

It was removed.

Line 131-132 – I really do not understand your description of water depth sampling. You classified the sampling sites based on their maximum depths? Where did you measure in the water column? If a site was 10 m deep, did you sample at 3 depths? Did you sample 0.3 m, 6 m, and 9 m? Be more explicit with your description here. Why did you pick 60% of max total depth for sampling?

The water column sampling method was as you have described. The sampled depths were related to the total depth of each site. These depths were chosen based on the variation of water speed and transport of suspended particles in the water column of rivers. Our 60% depth was a mid-depth sampling point to compare to surface and bottom waters. The three depths were sampled only in deeper sites where higher water velocity variation occurs. Since water flow and topography drives pressure gradients on sediment interface that affect particulate matter transport (Huettel et al. 1996). In shallow sites (depth <7,5 m) samples were only taken at 60% the depth. We revised this sentence to clarify the text and moved to headspace sampling description (L162-164).

Line 136 – state that the flooded areas sampled were in both reservoirs if that is the case.

Thank you, updated as suggested (L152-154).

Line 143 – 'according' not 'accordingly'

We corrected this word (L161).

Line 148 – what did you collect the headspace air in?

The samples from the headspace and atmospheric air were collected using 60 ml syringes and immediately transferred to evacuated glass vials closed with butyl rubber stoppers and sealed with aluminum crimps. The vials were evacuated immediately before transferring samples using a needle. We have updated this information (L169-171).

Line 150 – how were the gas samples transferred? Via needle and syringe because the vials were pre-capped, I presume.

Please see the above comment.

Line 154-156 – combine these two sentences into one

Thank you, we have made this change (L173-175).

Line 158 – if you made measurements from a drifting boat in a river, I presume you drifted quite a bit. Did you consider this drifting distance in your measurements of flux? This is an important point. How far did you drift? You need more details regarding this sampling approach.

Drifting distance was not measured during deployments. Based on visualization in Google Earth we estimate that the maximum distance drifted may be approximately 1 km for measurements in the river channel up and downstream of the reservoirs. In sheltered areas located in bays and over islands with standing trees, where the water flow was low, drifting was very short and caused by wind. An estimate of the drifting distance in the natural river channel and in the main channel of the Xingu Reservoir was obtained by using the average water velocity measured by the National Water Agency of Brazil at the Altamira station. We separated the historical values into before and after 2016, when the dams was completed. Therefore, representing estimates of water velocity in the natural river (between 2005 and 2016), and in the Xingu Reservoir main channel (after 2016). The average water velocities at Altamira are 0.74 and 0.24 m s^{-1} *for before and after the dam, respectively. Assuming that there is no resistance of the boat with the water or air, drifting speed is similar to the water velocity. The total time of deployment was up to 30 minutes for the three consecutive measurements. Based on these we found that in the main channel of the Xingu Reservoir the drifting distance would be 432 m, and 1332 m for the natural river channel up and downstream the reservoirs. These details were added to supplementary material.*

Line 161 – 'calculated' instead of 'done' and delete 'the eq. (1)'

Thank you, done (L182).

Line 168 – use 'erroneous' instead of 'same sampling site'

Thank you, the sentence was altered (L187-189).

Line 171 and eq. 2 – you say that k was based on the flux measurements but I do not see them in equation 2. I guess it is somehow in the partial pressure measurements since some are in the chamber but I think this needs a better explanation. You didn't find k using FCO_2, but rather using the concentrations in the chamber? That is how I perceive this equation.

Thank you, that is correct. The calculations were not made with fluxes, but with the CO_2 *partial pressures inside the chamber. We corrected this sentence in the manuscript (L193-194).*

Line 176 – need 'respectively' at the end of the sentence

We have altered this sentence (L198).

Line 177 – grammar is poor here

Thank you, sentence rewritten (L199).

Line 184 – give a bit more detail here about how the gas transfer velocities were not calculated from 2016 data. I am guessing it is because the other loggers did not allow it somehow, but I don't see why you couldn't perform the calculations using concentrations from those loggers too.

This sentence was removed, but the lack of gas transfer velocities for the high water season of 2016 is due to the lack of water pCO_2 *data in this campaign.*

Line 187-188 – I do not understand why or how these measurements were made according to the water depth classes. Do you just mean depths? And did you do this at each sampling site?

This part was changed. Depth profiles were done along the whole water column at each sampling site (see suplementary Figure S1). However, for testing the relationship between the physicochemical parameters and the pCO_2 *we have selected only the physicochemical data for the same depths where* pCO_2 *was measured. The depth profiles for* O_2 *and temperature for each environment are presented in the supplementary material.*

Line 199 – what does 'assessed separately by season' mean?

Thank you for the observation. That means that the statistical test was done using results for each season separately, since there was no inter-calibration among the different sampling method on each season.

Line 208 – you should restate here specifically that you are comparing high and low water from 2017 only.

We have added this statement as suggested (L230).

Line 208 – replace 'presented a significant variation' with 'varied significantly'

Thank you, we have altered this sentence (L231).

Line 221 – it gets confusing a bit when you go between comparing seasons to looking at the whole dataset so be specific when you can. For example, I would add 'From the overall dataset,' before 'Higher pCO_2 was registered..'

Thank you, we have re-evaluated this section to clarify the manuscript. This sentence was altered as suggested (L238). Whole paragraph was rewritten and reorganized.

Line 223 – I am confused by this sentence and what is respective to each other. Rewrite this one.

This sentences was rewritten as suggested (L238-240).

Line 228 – Because you only had pCO_2 data for 2017 then I guess you couldn't find a correlation between pCO_2 and FCO_2 in the 2016 data, correct? You need to specific again here and state that the correlation was only for the one method.

That is correct, we could not do this test for 2016 due to the lack of water pCO_2 *data. The correlation found between* pCO_2 *and* FCO_2 *corresponded to 2017. This sentence was rewritten, near-bottom results were added (L241-243) (Table 3).*

Line 232-234 – does it really matter if the two sensors were not cross calibrated in terms of absolute concentrations if it is just the slope of the increase of concentration over time that you need for flux calculations? If it is merely slope then you should be able to estimate and then compare the rates of flux, no?

This is correct, but because we were not able to do any intercomparison we chose to be conservative and evaluate them separately to avoid any source of error in our interpretations.

Line 235-237 – how is it that that the low water season had the highest and lowest FCO_2 values but was also homogeneous? This is very confusing.

The homogeneity in the FCO_2 *occurred when both reservoirs were evaluated together, however when each reservoir is considered separately the fluxes differed. Therefore, the pattern observed in low water season is driven by the reservoirs characteristics, not the spatial heterogeneity. In the low water season, the IR presented the highest* FCO_2 *that may be attributed to the presence of remainings of plant-derived material left from vegetation clearing. On the other hand, the* FCO_2 *in the XR decrease may be related to the natural seasonal pattern of* FCO_2 *observed in undisturbed rivers in the Amazon. The area of the XR is in its majority the original river channel where rocky and sandy substrates predominate (L372-385).*

Line 242-243 – this sentence is kind of just hanging here by itself. Shouldn't it belong somewhere in a paragraph.

We have removed this sentence.

Line 244 – I would rename this section a bit more specific to what you are doing: 'pCO_2 and FCO_2 in ROR versus storage reservoir'

Thank you, we have altered the section names properly since ROR and storage classifications are not used anymore.

Line 245-246 – if you consider the standard deviation of your measurements then I would say the differences are not so significant between seasons as they then overlap, especially for IR

Actually there was no statistical difference among reservoirs' pCO_2 *according season, therefore we removed this sentence. Conclusions had to be updated accordingly (L404-405).*

Line 249 – the difference in IR is much more significant than XR. I would point that out here.

Thank you, we have altered this sentence and removed those average values from the text. A summary of the average values is now presented in Table 2 (L263-264). The difference observed in the reservoirs are now pointed out by our statistical analysis (L269).

Line 250-252 – I don't understand what you mean here. You did a spatial analysis but lumped all spatially different environments together? I think you mean to say that you compared the total emission from XR to the total emission of IR despite the emitting environment. Is that right?

Thank you, this was exactly what we meant. We have better addressed this in the text (L261-263).

Line 252-255 – I don't understand how you see no significant difference between pCO_2 of XR and IR but then suddenly find that XR had pCO_2 721 uatm lower. And lower than what? I guess IR. These few sentences are very confusing.

The T-Test analysis was removed since it is related to a descriptive result.

Line 256 – You cannot just present an idea like ‘Standing vegetation type in XR flooded areas influenced pCO_2’ without explaining the data that led you to that conclusion.

Thank you. This sentence was modified to explain the data better (L254-255).

Line 264 – use ‘especially’ instead of ‘specifically’

This sentence was removed in results section rewriting.

Line 266 – what is a ‘gradient pattern downstream’??

We refer to the pattern of both pCO_2 and FCO_2 that are higher directly downstream the dam and decreases on the sites most distant from the reservoir. We have rewritten this sentence and removed this term (L257-259).

Line 272 – again with this ‘separately to each season’ – I still do not understand what this means. You have to come up with a better way of describing this.

This sentence was removed following referee 1 suggestion. But to explain, the FCO_2 data was measured using different equipment in 2016 (high water) and 2017 (high and low water), and we chose to evaluate them separately to avoid any potential source of error in the comparisons due to the lack of cross calibration. Thus the seasonal comparison was done using only data from 2017, when only the CO_2 loggers were used to measure the CO_2 fluxes.

Line 274 – use ‘without significant spatial heterogeneity across environments’

Thank you, we have modified this sentence as suggested (L274-276).

Line 275 – use ‘k_{600} strongly correlated with wind…’ and does this relate to Fig 5b? Should you reference this?

Yes, this sentence is related with fig 5b. The sentence was changed and table mentioned (L276-277).

Line 280 – there is not environmental breakdown in the data in Figure 5

Thank you, this reference was removed.

Line 287 – so you have water column data? Where is this data?

Depth profiles were made in 2016 and at the high water of 2017. You can find in the supplementary information a description about how it was done and Figure S1 showing the O_2 and temperature variation accordingly to type of environment

Line 303 – decrease in what?

This sentence seemed unnecessary and it was removed after posterior revision.But we meant that the pCO_2 decreased was due to the transition from high to low water caused by a lower organic matter input.

Line 344 – what is ‘vegetal suppression’? I figured out that it is when you remove vegetation prior to flooding but is this the correct term for this? It sounds very strange.

Vegetation clearing is the most adequate term. This was altered through whole text.

Line 344-345 – this sentence is too long with poor grammar

Thank you, this sentence was rewritten (L315-318).

Line 354-356 – combine those sentences

Done (L322-324).

Line 356 – how many of the environments? Do you mean all except IR? This is confusing. If it is just IR that ithe exception then you need to state it as 'all except IR'

Exactly, we observed an increase in FCO_2 *and* pCO_2 *at the low wate season for the IR only. The sentence was altered as suggested (L324-326).*

Line 357-358 – negative fluxes can be replaced with 'observed CO_2 uptake'

Thank you, done (L327).

Line 358 – 'light penetration and low suspended sediment'

Thank you, updated as suggested (L328).

Line 363-365 – you already spoke about this earlier. Try not to be redundant

We have altered this sentence detailing the influence of vegetation prior to flooding on the FCO_2 *(L379-380).*

Line 370 – need 'which' before 'would'

Done (L385).

Line 372-373 – I don't think you need these values here in the discussion.

We agreed, this sentence was removed.

Line 387 – can you give a site number for the 'site downstream IR'?

Absolutely, this site is P21. This information was updated in the manuscript (L338).

Line 391 – I don't think this true and I don't think you need this sentence about a reference for natural FCO_2 values

Agreed. We have removed this sentence.

Line 397-398 – do you mean that the downstream sites resembled river channel sites in terms of pCO_2 and FCO_2 values? Don't use 'traits' to describe this. Traits more refers to features that don't vary.

Yes, that was what we meant. However, we removed this sentence due discussion rewriting.

Line 408-409 – are you saying that the old reservoir you are using for comparison is Tucurui? The grammar here is confusing.

Exactly, Tucuruí reservoir was compared to both XR and IR. The sentence was rewritten (L360-362).

Line 412 – what do you mean by hypolimentical waters? It should be 'hypolimnetic' by the way. But this just means bottom waters with an implication of stratification, but what specifically do you want to express here?

We have removed this sentence.

Line 419 – bad grammar in last sentence

This sentence was unnecessary and removed.

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Relevant changes list

Referee 1 comments

Title, pg. 1.

Introduction:

Belo Monte controversies, pg. 3, lines 63-68.

Inland waters information updated, pg. 3, lines 40-44.

Reservoir carbon balance, pg. 3-4, lines 73-84.

Study hypothesis, pg. 4, lines 84-99.

Material and methods:

Reservoirs characteristics, pg. 4-5, lines 119-143.

Residence time corrections, pg. 5, lines 135-143.

ROR and storage classes removed.

pCO2 380 ppm base altered, pg. 6 lines 187-189.

Depth profiles, pg. 7, line 207.

PERMANOVA description, pg. 7, lines 219-221.

T-test analysis removed.

Results:

Unnecessary average values and comparisons removed.

Statistical results to near-bottom and surface depths, pg. 8-9, lines 241-243, lines 292-294.

Rewritten and reorganized, pg. 7-8, lines 230-246, lines 254-259.

Downstream site error corrected, pg.8, lines 257-259.

Rewritten and reorganized, pg. 8, lines 261-272.

Rewritten and reorganized, pg. 8, lines 274-278.

Conductivity minimum value corrected, pg. 9, line 290.

Discussion:

Seasonal discussion, pg. 9, lines 297-309.

Petit Saut comparison rewritten, pg. 10, lines 346-353.

Turbine activity discussion deleted.

K600 comparisons added, pg. 11, lines 388-393.

Discussion updated, pg. 11, lines 393-401.

Figure 3 updated, new panels added, pg. 18-19.

Table 2 literature values removed, pg. 23.

Table 3 added, pg. 24-25.

Table 5 added, pg. 25.

Supplement material added.

Referee 2 comments

Abstract:

Rewriting, pg. 2, lines 9-24.

Introduction:

Inland waters information updated, pg. 3, lines 40-44.

Belo Monte controversy added, pg. 3, lines 63-72.

Material and methods:

Reservoirs characteristics, pg. 4-5, lines 119-143.

Residence time corrections, pg. 5, lines 135-143.

ROR and storage classifications removed.

T-test analysis removed.

Sampling methods better detailed, pg. 6, lines 169-171.

Results:

Sub-section names altered.

Statistical results to near-bottom and surface depths, pg. 8-9, lines 241-243, lines 292-294.

Discussion:

Section divided in sub-sections.

Discussion rewritten and reorganized, pg. 9-11, lines 297-401.

Conclusions:

Updated according manuscript chances, pg. 11-12, lines 404-405.

Updated according manuscript chances, pg. 12, lines 406-408.

Figure 3 updated, new panels added, pg. 18-19.

Figure 5, added to supplement material.

Marked manuscript:

*Rewriting on results and discussion sections were not marked to avoid confusion, since it was too extensive (lines 230-246, 254-259, 261-272, 274-278 and 297-401).

Carbon dioxide (CO_2) 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 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. Its construction had received large attention from the media due to the social and environmental impacts related to its implementation. It is composed of two ROR reservoirs; the Xingu Reservoir (XR) in the Xingu mainstem and the Intermediate Reservoir (IR), an artificial reservoir fed by waters diverted from the Xingu River with longer water residence times compared to XR. We evaluated spatiotemporal variations of surface water CO_2 partial pressure (pCO_2), water-atmosphere CO_2 fluxes (FCO_2), and gas exchange coefficients (k_{600}) in the XR and IR during the first two years after the impoundment of the Xingu River. Season had a significant influence on pCO_2, with the highest average values observed during the high water season. Spatial heterogeneity was observed for pCO_2 during both low and high water seasons while FCO_2 showed significant spatial heterogeneity only during the high water period. The FCO_2 (0.90 ± 0.47 and 1.08 ± 0.62 µmol m^2 d^{-1} to XR and IR respectively) and pCO_2 (1,647 ± 698 and 1,676 ± 323 µatm to 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. In contrast, during the low water season FCO_2 (0.69 ± 0.28 and 7.32 ± 4.07 µmol m^2 d^{-1} to XR and IR respectively) and pCO_2 (839 ± 646 and 1,797 ± 354 µatm to XR and IR respectively) in IR were an order of magnitude higher than literature FCO_2 observations in clearwater rivers with natural flowing waters. CO_2 emissions from the IR were 90% higher than values from the XR during low water season, reinforcing the strong influence of reservoir characteristics on CO_2 emissions. Based on our observations in the Belo Monte hydropower complex, CO_2 emissions from ROR reservoirs to the atmosphere are in the range of natural Amazon rivers. However, the associated intermediate reservoir may overcome these emissions due to altered riverine characteristics. 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 CO_2 fluxes over their entire life cycle in order to improve estimates of CO_2 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 (CO_2) or methane (CH_4) 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), 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). Despite the relatively small area covered by inland waters, their carbon emissions offset the oceans carbon sink (1.42 ± 0.53 Pg C y^{-1}) (Landchützer et al., 2014).

Channel impoundment promotes several changes on 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 CO_2 (Battin et al., 2008). The intense decomposition of OM contained in flooded soils, in addition to the consumption of alochthonous OM deposited in the reservoir may lead to an increase of the CO_2 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 CO_2 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).

In order to minimize some of the impacts usually associated with hydropower dams, run-of-the-river (ROR) hydropower systems have smaller reservoirs and operate with seasonal variations in water levels (Csiki and Rhoads, 2010; 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). Great debate emerged from 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 (Fearnside, 2006). The discussions lasted at least 20 years and resulted in a series of changes and revisions in 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 on 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 planned to be built in the 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 CO_2 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 impoundment of the Xingu River channel, which has waters diverted to feed the Intermediate reservoir (IR), build by 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 flooding forest, but upland forest areas were also locally flooded in marginal areas. Vegetation was removed from most of the flooded areas, but part of the flooded forest islands in the XR were not cleared out. 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 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. This evaluation is crucial to understand GHG emissions from reservoirs in the eastern Amazon, a tropical region poised to gain 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 CO_2 partial pressure (pCO_2) and carbon dioxide fluxes to the atmosphere (FCO_2); 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 km^2 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 m^3 s^{-1} during the low water season and 18,983 ± 9,228 m^3 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 Vitória do Xingu Municipality (Fig. 2).

Belo Monte construction started in 2011, and reservoirs (Fig. 2) 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 at 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 later harbor the main powerhouse 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).

The reservoirs occupy together an area of 516 km^2. The XR extends over an area of 382 km^2 (Brasil, 2009b) from which 94 km^2 correspond 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 did not have vegetation clearing (Norte Energia, 2015). Differently, the IR occupies an area of 134 km^2 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):

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

Where RT is the water residence time given in seconds, and later converted into days, V is the reservoir volume in m^3 and Q is the volumetric discharge in m^3/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 CO_2 emissions in ROR reservoirs.

2.2 Carbon dioxide partial pressure (pCO_2) and CO_2 flux (FCO_2) 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 FCO_2:

(I) unaffected river channel: sites located on 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 mainstem 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 FCO_2 (Table 1).

During the year of 2017 (high and low water level seasons), values of pCO_2 in the water column were obtained using the headspace equilibration method according to Hesslein et al. (1991). The pCO_2 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 CO_2. All gas samples were then transferred using needles from syringes to evacuated glass vials pre-capped with butyl rubber stoppers. The pCO_2 data were acquired using a Picarro® G2201-i cavity ring-down spectroscopy (CRDS) and calculations were based on Wiesenburg and Guinasso (1979).

Diffusive CO_2 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 m^2 of area and 11.7 cm of height. The analyzer captures the change in CO_2 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, CO_2 mini-loggers (Bastviken et al., 2015) placed inside 6 L opaque (covered with reflexive aluminum tape) floating chambers with 0.07 m^2 of area and 10.5 cm of height were used to measure CO_2 fluxes. Sensors were placed inside the two chambers and deployed simultaneously during 20-30 minutes with a logging frequency of 30 seconds. CO_2 fluxes from water to the atmosphere were calculated according to Frankignoulle et al. (1998):

$$FCO_2 = \left(\frac{\delta pCO_2}{\delta t}\right)\left(\frac{V}{RT_K A}\right), \qquad (2)$$

The CO_2 flux (FCO_2) in mol CO_2 m^{-2} s^{-1} is given by the changes in pCO_2 inside the chamber during the deployment time ($\delta pCO_2/\delta t$, µatm s^{-1}), taking into account the chamber volume (V, m³), the universal gas constant (R, atm m^3 mol^{-1} K^{-1}), water temperature (T, K) and the area covered by the chamber (A, m^2). Measurements were discarded when the R^2 of the linear relation between pCO_2 and time ($\delta pCO_2/\delta t$) were lower than 0.90 ($R^2 < 0.90$) or had negative FCO_2 values with surface pCO_2 higher than atmospheric pCO_2 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, pCO_2 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 CO_2 was estimated based on the surface water CO_2 concentration inside the floating chamber by Eq. (3):

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

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 K0 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):

$$k_{600} = k_{\mathrm{T}} \left(\frac{600}{Sc_{\mathrm{T}}}\right)^{-0.5}, \tag{4}$$

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:

$$\mathrm{Sc_T} = 1911.1 - 118.11\,\mathrm{T} + 3.4527\,\mathrm{T}^2 - 0.041320\,\mathrm{T}^3, \tag{5}$$

2.4 Physical-chemical characteristics

Depth profiles with a measurement interval of 1m were for done for water temperature, pH, dissolved oxygen (DO) and conductivity using a multiparameter probe (EXO2®, YSI). During the high water in 2016 and 2017 samplings campaigns, Technical challenges prevented measurement of pH, dissolved oxygen (DO), and conductivity during the 2017 low water sampling. To statistical analysis these measurements were selected following the same water depth classes applied to pCO_2 measurements (surface, 60% and near 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 CO_2 variables (FCO_2 and pCO_2) and water column characteristics (pH, dissolved oxygen (DO) and water temperature) and to evaluate the spatial and seasonal variation of FCO_2, pCO_2 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 FCO_2, pCO_2,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 FCO_2 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 FCO_2 *versus* pCO_2, FCO_2 *versus* wind speed, k_{600} *versus* wind speed and pCO_2 *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 pCO_2 and FCO_2

The mean pCO_2 from areas upstream and downstream the dams was 1,163 ± 660 µatm. Based on 2017 data, pCO_2 values differ significantly between seasons ($F_{1:56}$= 9.77, R²= 0.09, p= 0.0045), showing higher pCO_2 in the high water season (1,391 ± 630 µatm) than in the low water period (976 ± 633 µatm) (Fig. 3a).The type of environment also had a significant role in pCO_2 distribution throughout the area affected by the reservoirs ($F_{3:56}$= 13.36, R²= 0.37, p= 0.0002). During the high water season, the highest average pCO_2 was observed downstream of the dams In contrast, during the low water season, the highest average pCO_2 values were found in the reservoirs over the flooded areas. Unaffected river channel categorized areas had the lowest pCO_2 a in both seasons (Fig.3).

Evaluation of the overall dataset, considering combined data from both seasons, higher average pCO_2 was registered near bottom (1,269 ± 689 µatm) in relation to average values from water surface (998 ± 613 µatm) (Table 2), characterizing significant influence of water depth on pCO_2 ($F_{2:56}$= 4.06, R²= 0.07, p= 0.0261).

Surface pCO_2 was positively correlated with FCO_2 both during the high water (r= 0.80; p= 0.0009) and low water (r= 0.71; p= 0.012) seasons (Fig.3). Near bottom pCO_2 showed correlation with FCO_2 only during 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). The average FCO_2 for all sites sampled during 2016 and 2017 high water seasons was 1.38 ± 1.12 µmol CO_2 m^{-2} s^{-1}, with similarity between years ($F_{1:28}$= 0.09, R²= 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 ± 3.21 µmol CO_2 m^{-2} s^{-1}) and lowest (-0.52 µmol CO_2 m^{-2} 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, R²= 0.43, p= 0.0089) while the low water season had relatively homogeneous FCO_2 values ($F_{3:17}$= 2.67, R²= 0.14, p= 0.08) (Fig.4 and Table 3). The highest (2.89 ± 1.74 µmol CO_2 m^{-2} s^{-1}) and lowest (0.84 ± 0.42 µmol CO_2 m^{-2} s^{-1}) average FCO_2 respectively occurred in sectors downstream of the dams and on flooded areas sampled during the high water season. Negative CO_2 fluxes were observed during the low water season in the river channel, exclusively (Table 2 and Fig.4).

In addition to the spatial heterogeneity, pre-existing vegetation cover influences pCO_2 and FCO_2 in the XR. Areas previously covered by pasture, upland forest and seasonally flooded forest had different pCO_2 concentration. Likewise vegetation cover, the XR and IR influenced downstream emissions promoting a trend of decreasing pCO_2 and FCO_2 downstream from the dams. This trend is demonstrated by lower average pCO_2 and FCO_2 values in downstream sites of the XR and IR, respectively at 90 and 25 km downstream of Pimental and Belo Monte dams, in relation to values measured upstream, in sites near the dams' outflow (Table 2).

3.2 pCO$_2$ and FCO$_2$ in the reservoirs

The spatial variability of pCO$_2$, 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 pCO$_2$ presented higher values in the XR during the high water season, while the opposite pattern occurred in the IR (Table 2).

XR and IR showed no significant difference for pCO$_2$ ($F_{3:56}$= 0.34, R^2= 0.009, p= 0.8170), 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). As observed for pCO$_2$, 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 ± 4.06 µmol CO$_2$ m^{-2} s^{-1}) during the low water season while the XR presented low FCO$_2$ (0.69 ± 0.28 µmol CO$_2$ m^{-2} s^{-1}). Despite variations in FCO$_2$ and pCO$_2$, 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 ± 24.0 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 ± 0.88 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 were observed 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 ± 0.73 mg L^{-1} in the unaffected river channel and lowest concentration in flooded areas (5.44 ± 2.00 mg L^{-1}) (Table 4). Water conductivity varied from 20.60 to 38.30 µS cm^{-1} in the studied environments, with the highest average value (31.60 ± 8.63 µS cm^{-1}) recorded in flooded areas and lowest value (29.30 ± 4.85 µS cm^{-1}) in 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 correlated (Rasera, et al., 2013), in this study was observed some specific examples where k produces different fluxes even when pCO_2 was similar. 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). In the studied area, significant changes of pCO_2 were observed between high and low water seasons as well as in terms of physiographic-hydrologic environment, as described previously, with these differences influencing FCO_2 values. The increase in pCO_2 during the high water season 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 (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 large CO_2 production during the initial years of impoundment (Guérin et al., 2008). In addition, the seasonal input of autochthonous and allochthonous organic material depositing in the reservoirs with higher water RT would result in remarkable seasonal changes in the pCO_2 and CO_2 fluxes from reservoirs to the atmosphere.

The oversaturation in CO_2 observed for XR and IR during high water conditions was spatially heterogeneous (Table 2). For 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 out of 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 most of pCO_2 and FCO_2 decreased, especially in the river channel environment, resulting in homogeneous FCO_2 due to photosynthetic activity in all environments with exception to the IR (Table 2). In addition, the CO_2 undersaturation in relation to atmosphere and observed CO_2 uptake may be attributed to elevated primary productivity, which is facilitated due to the high light penetration, and 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 CO_2 fluxes was observed only in unaffected river channel, on the furthest downstream studied site. This pattern can be related to the downstream decrease in suspended sediments due to increased sediment deposition in the reservoirs. Also, CO_2 fluxes in the XR and IR can 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. Furthest downstream sites situated 90 and 25 km downstream the XR and IR, respectively, presented average pCO_2 and FCO_2 lower than XR river channel. The upstream XR sites also had higher FCO_2 than observed in undisturbed sectors of other large clearwater rivers in the Amazon (Table 2). The site downstream IR (P21) is within the river extent (< 30 km) that could still be affected by the reservoir, as observed downstream of the Balbina reservoir, also in the Amazon (Kemenes et al., 2016). However, the XR should have a minor effect over the site further downstream due to its longer distance (90 km) from the dam outflow, and the presence of many large rapids and waterfalls in the Volta Grande region, quickly degassing the dissolved CO_2 coming from the upstream reservoir. The decrease in pCO_2 and FCO_2 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 reaches downstream of the Belo Monte dams have CO_2 emissions similar to observations from previous studies, with emissions also decreasing downstream (Abril et al. 2005; Kemenes et al. 2011).

In comparison to CO_2 emissions of river reaches downstream of tropical storage reservoirs, the FCO_2 measured for the Sinnamary River downstream of the Petit Saut reservoir in French Guiana was 10.49 ± 3.94 µmol CO_2 m^{-2} s^{-1} (Guérin et al. 2006), which is more than three times the average downstream FCO_2 (2.89 ± 1.74 µmol CO_2 m^{-2} 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 CO_2-rich bottom waters that increase downstream emissions through turbine passage (Guérin et al., 2006; Kemenes et al., 2011; 2016). However, the Belo Monte hydropower facility operates as ROR and has waters mixed without stratification and lower CO_2 oversaturation than in the Petit Saut reservoir, likely due to vegetation clearing.

4.2 pCO_2 and FCO_2 on Belo Monte reservoirs

In this study, the IR presented an average FCO_2 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 large forested islands flooded. 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. CO_2 emissions from the IR during the low water season were even above the range of emissions observe in storage reservoirs in the Amazon as

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 ± 1.62 µmol CO_2 m^{-2} s^{-1} to the atmosphere (Lima et al., 2002). In comparison to the XR (FCO_2 = 0.69 ± 0.28 µmol CO_2 m^{-2} s^{-1}), the Tucuruí reservoir presents higher FCO_2. However, this is three times lower than the FCO_2 (7.32 ± 4.06 µmol CO_2 m^{-2} 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 on IR the whole in the extension the land cover was cleared. The FCO_2 and pCO_2 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 CO_2 emission on both reservoirs during high water, however, the CO_2 emission from the IR is higher during low water, exceeding the fluxes of the Amazon River (Table 2) (Table 5). When analyzed separately, the average FCO_2 values observed for the XR and IR overcome these natural emissions. Based on the Belo Monte case, ROR dams are a CO_2 source to the atmosphere similar to natural rivers during high water season. However, the associated reservoir may promote increased CO_2 emission during the low water season compared to natural emissions from river channels.

CO_2 emissions may be correlated with prior vegetation flooding, with higher FCO_2 occurring in areas with the highest carbon stocks such as forests and wetlands (Teodoru et al., 2011). Although vegetation was cleared in the IR prior to flooding, the upper soil layer may have kept a high concentration of plant-derived material fuelling emissions. This condition explains the higher average pCO_2 in IR compared to XR, with the former area also having higher average FCO_2 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 in range of the Furnas reservoir, in the Grande River draining the Cerrado biome (savanna), which has k_{600} of 19.58 ± 2.5 cm h^{-1} (Paranaíba et al., 2017). This value is similar to k_{600} obtained in this study for the XR (22.99 ± 8.00 and 22.89 ± 21.40 cm h^{-1} on high and low water seasons, respectively). In counterbalance, the IR has k_{600} of 7.13 ± 1.5 cm h^{-1} (high water), which resembles gas transfer of the lake 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, FCO_2 values were higher in the main channel environment, where in addition to the relatively stable water flow due to the

ROR type reservoir, it 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 FCO_2 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 FCO_2 (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 coefficient 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 CO_2 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 CO_2 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 CO_2 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 CO_2 emissions similar to Amazonian clearwater rivers without impounding and considerably lower emissions than the several other tropical reservoirs that have been studied. However, CO_2 emissions during the low water season were higher than natural emissions and the IR CO_2 fluxes exceeded emissions measured in storage reservoirs of other tropical rivers. Despite the removal of the vegetation, the IR presented the highest CO_2 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 present 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, as 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 design 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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