October 22nd, 2019

Dear Dr. Clare Woulds

Thank you for the opportunity to submit the revised version of our manuscript. Please, find it attached. We have addressed all the comments and suggestions made by the two reviewers, which have considerably improved our manuscript. All the changes we made to the text are marked as bold and red. Based on reviewers' comments we decided to split the results and discussion sessions and we believe that this change made the manuscript easier to follow. We also added to the main manuscript one figure from the Supplementary Material (current Figure 5).

We hope our manuscript is now suitable for publication on Biogeosciences.

On behalf of the other authors,

Gabrielle Quadra (gabrielle.quadra@ecologia.ufjf.br)

RESPONSE TO REVIEWER 1

➔ **General comments:**

❒ **This is an interesting study on an important topic and for an understudied set of ecosystems (tropical reservoirs). I was impressed by the efforts at taking and analyzing more than a hundred sediment cores for a single reservoir and applaud authors for such a system focused analysis – there is still too few comprehensive studies based in a single system. I, however, also have some reservations that preclude immediate positive recommendation: first I was confused by your method description, particularly your estimate of sediment accumulation rates and your interpolations. This needs to be clarified.**

Response: Thank you for the positive comments and for pointing out the need for more detailed information on our methods section. We carefully revised the "Data analysis" section, adding more information especially about sediment accumulation and organic carbon burial calculations (where we added equations), and about interpolation.

$$Sediment\ accumulation\ rate = \frac{\text{sediment thickness}}{\text{reservoir age}}$$

$$Organic\ carbon\ burial\ rate\ = \frac{\text{Organic carbon mass in the post} - \text{flooding sediment}}{\text{core area} * \text{reservoir age}}$$

❒ **Along the same lines, I understand the need for fast publication but this dataset requires/deserves some more consideration – you mention pre and post--- flooding intervals but there is little mention on this in the discussion. You basically focus your entire discussion on comparison to previously published data with many detailed**

numbers provided – I do not think this necessary. The ms would be much stronger if you would make a clear case that large inputs from a highly productive forest produce large C burial and CH4 emissions. Massive CH4 production and emission in sediments supplied with lots of OM and particularly in hot tropical conditions is a stand---alone argument. This is also, as far as I see, not so much an oxygen/stratification driven effect but rather effect of high productivity – which is, in fact, interactive. You do not need to compare your findings to those from many other reservoirs and if you decide to do so, focus rather on processes and ratios than on absolute numbers.

Response: We appreciate and fully agree with this comment. We carefully revised the manuscript reducing the unnecessary comparisons with other studies and focusing more on our results. Based especially on this comment, we decided to split the Results and Discussion section in the revised manuscript. The discussion is now more straightforward and, thus, easier to follow. As suggested, the comparisons with other studies are now focusing rather on the processes occurring in other biomes. We also extended the discussion about the especially high productivity combined with the high temperatures of the Amazonian biome.

❒ **The manuscript is well written but some sentences are a bit too complex and should be re---written. I suggest that the entire text would benefit from a careful editing (I spotted some minor typos) and streamlining.**

Response: We revised the entire manuscript, and we are confident that the text has been improved.

➔ Specific comments: Introduction

❒ ***However, most of the CH4 is emitted from reservoirs via ebullition (i.e., gas bubbles), which is very difficult to measure due to its strong variability in space and time (McGinnis et al., 2006; 20 Deemer et al., 2016).*** **This is a very generous statement about ebullitive fluxes but nor necessarily correct. Some compact sediment do not allow for large bubble accumulation despite high methane concentrations. Ebullition is not always major emission pathway. Please re-phrase this sentence.**

Response: While there is evidence that ebullition indeed is the major CH_4 emission pathway in many reservoirs (Deemer et al. 2016 Bioscience), we agree that we should be more balanced in this statement. We changed this sentence, which now reads: "*However, in many reservoirs, CH4 ebullition (i.e., gas bubbles) is an important or dominant emission pathway, but it is very difficult to measure due to its strong variability in space and time (McGinnis et al., 2006; Deemer et al., 2016).*"

➔ Methods:

❒ ***Measurements with a multiparameter sonde (YSI 6600 V2)… showed that the relatively shallow water column (mean depth: 6 m) is generally well mixed.*** **I am not sure whether YSI profiles can give you a good measure of stratification/mixing and besides this is a discussion already. Please state you results and revise the text.**

Response: We understand your concern but we are confident that our YSI profiles can accurately indicate the lack of stratification during our samplings. The water column profiles of dissolved oxygen and temperature show that there are no big differences between surface and bottom waters, and thus that the water column is not strongly stratified for any extended period of time. This is important information related to CH_4 production. We therefore now include all the raw data in the supplementary information (total of 28 depth profiles spread along the reservoir during the two field campaigns), moved this sentence from the Methods to the Results, and rephrased it: instead of speaking of a well-mixed water column, we now say that the water column profiles indicate a lack of stable stratification over any extended periods of time. It is also worth to mention that our sonde was calibrated before each fieldwork and we thus have confidence in the measurements.

❒ ***In each of these cores, the first and second layer (0 to 4 cm deep), the last sediment layer above the pre---flooding soil surface, and about one sample every 8 cm in between were analyzed.* Why these intervals? Briefly explain or clarify sampling design.**

Response: Due to limited time and resources for chemical analysis, and since the OC content of sediment is prone to decrease during microbial degradation, we chose to analyze representative samples of the fresh material (surface sediment layers) and old material (bottom sediment layer), as well as some layers of intermediate age. From these measurements, the OC content of the non-measured layers was linearly interpolated from the measurements. Similar approaches have been used in previous studies, e.g. Mendonça et al. 2014.

We changed this part of the text in the manuscript for: "*OC and total nitrogen (TN) concentrations were determined in the 19 cores, which were distributed across the reservoir area. In each of these cores, the first and second layers (0 to 4 cm deep, containing the fresher OC), the last sediment layer above the pre-flooding soil surface (containing the older OC) and one sample every ~8 cm in between (OC of intermediate age) were analyzed.*"

❒ ***Using a core liner with side ports, 2 ml of sediment were collected using a syringe with a cut---off tip, added to a glass vial with 5 ml of distilled water, and closed with a 10 mm thick butyl rubber stopper.*** **We use similar method to evaluate sedimentary CH4 but samples are killed with concentrated NaOH solution, how does it work with DI water?**

Response: We used distilled water because there was no need for sample preservation. Instead, we equilibrated the slurry (2 mL sediment + 10 mL distilled water + 13 mL headspace of ambient air) immediately after sampling by vigorously shaking the 25 mL glass vial, and then transferred the gas phase to syringes immediately on the boat. The gas phase was stored in the syringe, closed with a gas-tight valve, and we injected the gas into the analyzer within the same day. We revised the manuscript text accordingly in order to clarify.

❒ ***The CH4 concentration in pore water was measured by an Ultraportable Greenhouse Gas Analyzer (UGGA, Los Gatos Research) with a custom---made sample injection port, and the peaks were integrated using an R script.*** **I believe that what you want to say here is that headspace concentrations of CH4 were measured with UGGA and the re---calculated to pore---water concentrations**

Response: Yes, exactly. We rephrased the sentence as follow: "*The headspace CH_4 concentration was measured by an Ultraportable Greenhouse Gas Analyzer (UGGA, Los Gatos Research) with a custom-made sample injection port, and the peaks were integrated using R software (RStudio Version 1.1.383). The CH_4 concentration in the pore water was calculated from the headspace CH_4 concentration, based on the Henri's law constants.*"

❒ ***Assuming that a CH4 concentration >80% of saturation concentration is indicative of a sediment layer prone to contain a gas bubble; this assumption mirrors the potential loss of gas from the sediment during coring and sampling.*** **Any literature to support this?**

Response: We wanted to account for the expected loss of bubbles during coring and sampling, and chose 80% saturation as an arbitrary threshold, because we could not find any literature on the quantitative loss of gas bubbles during gravity coring and sampling. However, as the 80% threshold was a concern of both reviewers, we chose to use 100% saturation instead; the difference in the number of oversaturated layers was very similar between the 80% and 100% threshold anyway (22 and 20 sites of 25, respectively). Importantly, given that our method certainly underestimates bubble (and thus CH_4) content of the sediment, our conclusions regarding the potential for CH_4 ebullition are conservative. We revised the text accordingly.

❒ ***The average sediment accumulation rate (SAR; cm yr---1) was obtained by the ratio of post---flooding sediment thickness and the reservoir age.*** **Same here. Do you have any support for this method to estimate sediment accumulation rate? What about movement of sediments or turbidities? Do you have a photo of your sediment cores? Did you try to date them?**

Response: The approach we used to estimate sediment accumulation rate was used, for example, in the studies by Renwick et al. 2005, Kunz et al. 2011, Mendonça et al. 2014 and Quadra et al. 2019. These references were added to the manuscript. This approach considers that the layer of transition between pre- and post-flooding sediment corresponds to the year when the dam was closed and the reservoir was flooded. This moment is the onset of a lacustrine depositional regime, which is characterized by different sediment texture and composition in relation to the pre-flooding soil or fluvial sediment. Therefore, this transition layer is easily identified visually. We added photos of the core aspect to figure S2, where we show that the transition is clear (see below). The approach we used considers only two dates

– the year of reservoir flooding (the bottom of the post-flooding sediment) and the year of sampling (top sediment layer). Therefore, the sediment accumulation rate we estimate from sediment thickness (cm) and reservoir age (yr) represents an average over the reservoir lifetime. This average, thus, includes any temporal variability in sediment deposition caused, for example, by change in sediment load or internal sediment movement. As we sampled a large amount of cores distributed along the reservoir body, we assume that we captured, the best way possible, the spatial variability in sediment deposition due to sediment focusing (sediment movement with preferential deposition in deeper areas).

We did not use radioisotopes (e.g. 210Pb) for dating, since also these methods suffer from uncertainties, rely on the choice of model for interpretation of activity profiles, and are affected by sediment mixing. Another very commonly used radioisotope, 137Cs, is very similar to the method used by us, because it considers the difference between years to calculate average sediment accumulation between these dates (in the case of 137Cs, between the Chernobyl accident 1986 or the peak of atmospheric nuclear weapon testing 1963, and the year of coring). For these reasons, we argue that our method does not produce less reliable data than other methods.

<u>New References:</u>

Renwick WH, et al. (2005) The role of impoundments in the sediment budget of the conterminous United States. Geomorphology, 71(1-2), 99-111.

Quadra GR, et al. (2019) Environmental Risk of Metal Contamination in Sediments of Tropical Reservoirs. Bulletin of Environmental Contamination and Toxicology, 1-10.

Figure S2. Pictures with sediment cores of Curuá-Una reservoir showing the transition zone between pre-flooded (gray color) and post-flooding (brown color) sediment.

❒ ***SAR was positively correlated to OC burial rate in the sites.* Isn't this implicit from the method you used to calculate SAR and OC burial. You used total OC – which is clearly a function of sediment thickness to calculate burial and then you used thickness directly to calculate SAR? Either I am confusing something or both of these functions use the same dataset.**

Response: While the total OC inventory can be a function of sediment thickness, this does not need to be the case, since different kinds of sediment can have very different OC content; a quite thin but OC-rich sediment (e.g. algae remains) can have the same inventory as a very thick but OC-poor sediment (e.g. sand). In our case, SAR and OC burial strongly correlate, probably because the sediment not very heterogeneous. The regression in the manuscript is to show that, regardless of sediment OC content, OC burial can be predicted from SAR, which can be more easily estimated from visual analysis of the sediment cores, without the need of laboratory analysis of sediment density or OC content.

❒ ***used to estimate the OC burial rate (g C m---2 yr---1) from SAR for the coring sites where OC content was not analyzed.*** **Ok. I am a bot confused here. Please indicate here for how many sites you have the data and how many were treated to this interpolation.**

Response: In the new version of the manuscript, we explained it better adding the details the 'Data analysis' section. We took 114 cores and all of them were analyzed for sediment thickness and SAR. 19 of these 114 cores were also sliced and analyzed for OC content and OC burial rate. From the regression between SAR and OC burial rate, we estimated OC burial for the remaining 95 cores, which were not analyzed for OC content.

➔ **Results and Discussion**

❒ **I think that this section can be much reduced by clearly discussing new findings and possibilities as well as perhaps some more quantitate analysis of inputs, Currently there is too much comparison to previous research and too little insight into the implications of this study. The work is valuable and has a potential for impact but more work in this section is needed.**

Response: Thank you for pointing this out, and we agree. We decided to split Results and Discussion section in the revised manuscript, as we believe that this will make the text more clear and easy to follow including a discussion that more coherently concentrates on the new findings. For example, we now only cite previous studies in order to illustrate our findings, not for mere comparison of quantities. Also, the discussion is now organized by findings, and no longer by measured parameter (as it was in the Results and Discussion section of the original submission).

❒ **Figure 3: perhaps a mass balance for sedimentary CH4 would be informative here?**

Response: While a mass balance would be interesting, we are not able to calculate it using our data. To calculate the mass balance, we would need the CH_4 input and output rates, which we cannot estimate from the measured pore water concentrations.

RESPONSE TO REVIEWER 2

➔ General comments:

❒ This paper estimates organic carbon (OC) burial and describes patterns in sediment methane concentration based on extensive sediment coring (114 cores over two time periods) in an oligotrophic Amazonian reservoir. The authors describe their data set as unique given 1.) the lack of studies that look at both organic carbon burial and methane concentration/emission dynamics and 2.) the lack of Amazonian studies focused on reservoir organic carbon burial. While there is a lack of organic carbon burial estimates from reservoirs (relative to the number of greenhouse gas emission estimates), I think the authors have somewhat overstated the novelty of their findings (at least in terms of the magnitude of OC burial they report). For example, I am confused as to why the authors classify their reported burial rates as "high" (e.g. in the title of the paper and elsewhere). The mean rate of 91 g C m-2 yr-1 they report appears to be more towards the lower end of the reservoir OC burial rates reported by Mendonca et al 2017 (looking at Figure 1 of that paper). Also, while studies that have looked at both OC burial and greenhouse gas emission are rare, the ones that exist should be discussed.

Response: Thank you for the positive and constructive comments. The OC burial rate we found in Curuá-Una reservoir is high if compared with other tropical hydroelectric reservoirs. In fact, as we stated in the abstract, this is the highest OC burial rate in a tropical hydroelectric reservoir reported so far. The global study by Mendonça et al. 2017 included, as "reservoirs", agricultural ponds and fish farms, which usually have extremely high organic carbon burial rate, and which we do not compare with, because they are completely different systems in terms of hydrology and size. In order to make the context of the word "high" clearer, we added the word “hydroelectric” to the title, restricting the type of system we are focusing on. The title now reads: “*High organic carbon burial but high potential for methane ebullition in the sediments of an Amazonian hydroelectric reservoir*”. We also checked the entire text to make sure that the connotation of high burial applies in comparison to other hydroelectric reservoirs at low latitudes.

❒ **I recommend that the authors reference Jacinthe et al. 2012 and Teodoru et al. 2012 as part of this discussion.**

Response: Jacinthe et al., 2012 worked in a different climatic and geographic context, a reservoir in a temperate agricultural landscape, and we decided to keep the discussion limited to the context of low-latitude reservoirs (see also our reply to reviewer #1). We are now citing Teodoru et al., 2012 in the new discussion, even though it is a study of a reservoir in Canada, since it presents data on the balance between emission and burial, which has rarely been done. Adding to our study the emission estimate of Duchemin et al., 2000, we found that sediment C burial represented around 15% of C emission, while Teodoru et al., 2012 found that C accumulation represented around 10% of the reservoir emissions. Moreover, we are now using Stratton et al., 2019 to argue about OC burial variability in space and time and, consequently, the importance to represent different regions in the aquatic systems to estimate C burial.

<u>New References:</u>

Duchemin É, et al. (2000) Comparison of greenhouse gas emissions from an old tropical reservoir with those from other reservoirs worldwide. Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen, 27(3), 1391-1395.

Stratton LE, et al. (2019) The importance of coarse organic matter and depositional environment to carbon burial behind dams in mountainous environments. Journal of Geophysical Research: Earth Surface.

❒ **Overall, I think this dataset is quite novel and worthy of publication, but the presentation and data analysis deserve more time and thought than has currently been invested. For example, the positive relationship between sediment methane concentrations and sediment OC burial (currently reported as a figure in the supplement) seems worthy of its own figure and of more interpretation.**

Response: Thank you for the suggestion. We have now made a separate figure for that in order to explore the relationship. Although the correlation is not very strong, we observed that a high burial rate was positively related to a high number of samples (as percentage of total samples in each core) above the CH_4 saturation concentration. Moreover, we are now splitting the Results and Discussion section, which allows a more comprehensive discussion of our findings (see also our reply to reviewer #1).

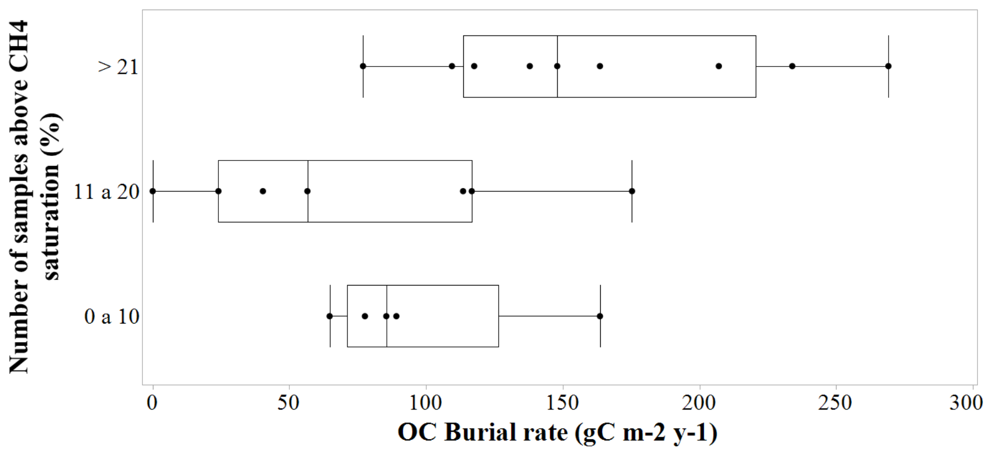

Figure. Boxplots of percentage of sediment layers with CH_4 concentration above saturation (%) and OC burial rate (gC m^{-2} y^{-1}).

❐ **It is also interesting that the sediment methane concentrations did not differ significantly between the rising and falling limb of the reservoir hydrograph. This finding could be highlighted more in the context of other work that has been done to look at water level as a driver of methane emission.**

Response: We agree and are now citing some papers (Mattson & Likens 1990; Eugster et al. 2011; Maeck et al. 2014) on the influence of water level or pressure changes on CH_4 ebullition in relation to this observation.

<u>New References:</u>

Mattson MD, et al. (1990) Air pressure and methane fluxes. Nature, 347(6295), 718.

Eugster W, et al. (2011) Eddy covariance flux measurements confirm extreme CH (4) emissions from a Swiss hydropower reservoir and resolve their short-term variability. Biogeosciences, 8(9), 2815-2831.

Maeck A, et al. (2014) Pumping methane out of aquatic sediments: Ebullition forcing mechanisms in an impounded river. Biogeosciences, 11(11), 2925-2938.

❐ **I am also surprised that the authors haven't placed their findings in the context of other work that has been done on Curua Una to estimate GHG emissions (Duchemin et al. 2000). Duchemin and colleagues estimated 42.5 mg CH4-C m-2 d-1 ebullitive + diffusive emissions, which could be compared to the C burial estimated in this study via CO2-equivalents.**

Response: In response to this suggestion, we have added a comparison of our findings to the emission estimate published by Duchemin et al. 2000. We added this information in the manuscript: "*The OC burial rate found in CUN is high comparing to other tropical hydroelectric reservoirs (Sikar et al., 2009; Kunz et al., 2011; Mendonça et al., 2014). However, our OC burial estimate represents only 15% of the total carbon emission previously reported for the CUN reservoir (509 g C m^{-2} yr^{-1}, Duchemin et al. 2000). Similarly, a study conducted in a boreal Canadian reservoir found that OC burial corresponded to 10% of reservoir C emission (Teodoru et al. 2012). It seems that in both reservoirs, emission is much higher than burial, even though burial was about 10 times higher in CUN than in the Canadian reservoir (9.8 g C m^{-2} yr^{-1}).*

❒ **Line 22: add "and emitted" after "produced"... it is important to be clear that production is different than emission**

Response: We changed this sentence accordingly: "*Reservoir sediments sequester significant amounts of organic carbon (OC), but at the same time, high amounts of methane (CH_4) can be produced and emitted during degradation of sediment OC.*"

❒ **Lines 23-25: this sentence is rather vague and doesn't add very much to the abstract as currently written. I suggest highlighting the lack of studies that look at both OC burial and GHG emission in reservoirs with no studies focused in the Amazon**

Response: We changed the statement for: "*There is a lack of studies focusing on OC burial and GHG emission, with no studies in the Amazon. Hydropower is expanding in the Amazon basin and understanding its biogeochemical processes and impacts are crucial for decision makers*".

❒ **Line 34: change "indicate" to "suggest"**

Response: Changed accordingly.

❒ **Line 51: change to "estimates of"**

Response: Changed accordingly.

❒ **Lines 63-64: Maybe describe regions where there is a particular lack of OC burial data? Also, you might describe briefly the difference between total C burial and organic C burial somewhere here (since you are focused on organic C rather than carbonates).**

Response: Thank you for the comment. We will modify the sentence for: "*In particular, large regions of the Earth are at present completely unsampled concerning inland water carbon burial. Approximately 90% of the sites sampled for carbon burial are in North America and Europe, while there are only few measurements in South American and Asian countries (Mendonça et al. 2017).*"

Our study focused on organic carbon burial because of its importance to carbon sequestration and CH_4 production in inland waters. We make sure that this is clear in our text and we prefer not to mention the carbon fractions that were not studied or discussed in the paper.

❒ **Line 86: The fraction of methane that is emitted via ebullition vs. diffusion varies from system to system (where ebullition is not always the dominant pathway).**

Response: We have changed the wording of this sentence (see also our reply to reviewer #1), to become more balanced as to the relative magnitude of emission pathways. The sentence now reads: "*However, in many reservoirs, CH_4 ebullition (i.e., gas bubbles) is an important or dominant emission pathway, but it is very difficult to measure due to its strong variability in space and time (McGinnis et al., 2006; Deemer et al., 2016).*"

❒ **Line 95: First whole-reservoir OC burial estimate in what context? In an Amazonian**

reservoir? Clarify.

Response: This sentence was clarified to: "[…] *to present the first whole-reservoir OC burial estimate and the first mapping of concentrations of CH_4 in sediment pore water in an Amazonian reservoir"*.

❒ **Lines 129-130: How did you spatially distribute the cores? Randomly? Stratton et al. 2019 is a good reference for the importance of sampling across multiple regions of the reservoir (which is not done often — more often burial estimates are collected from a single site/region).**

Response: We distributed the sampling sites in a way to have them approximately evenly distributed, covering the reservoir as much as possible, and taking samples from multiple regions, both longitudinally and laterally, as suggested by Stratton et al. 2019. We have clarified the text and added the reference.

❒ **Figure 1: I think the inset map would be more helpful for an international readership if the whole shape of South America was shown (rather than just Brazil).**

Response: We changed the figure accordingly.

❒ **152: change "exactly" to "exact" 154: omit word "approximately"**

Response: Changed accordingly.

❒ **Lines 166-168: What did you do after adding acid? Was this a qualitative test (looking for evidence of fizzing?) or did you re-analyze for C after adding acid?**

Response: This was a qualitative test and we added this information in the manuscript: "*The* *presence of carbonates was checked in the samples qualitatively by adding drops of acid, and no evidence of solid carbonates was found".*

❒ **Lines 179-188: Did you measure atmospheric CH4 concentrations here? More detail on the equations/calculations would be helpful.**

Response: Yes, we measured the atmospheric CH_4 concentration from air samples taken at the same location as the cores were sliced, and used as background in the calculations. More specifically, we subtracted the atmospheric CH_4 mass from the total CH_4 mass in the equilibration vials. We now added more details on the calculations to the methods section, as well as references of other studies that used the same approach (Sobek et al., 2012; Mendonça et al., 2016).

❒ **Line 181: I don't think it is necessary to mention "an R script" unless you are citing a specific existing R package.**

Response: Changed accordingly.

❒ **Lines 190-194: Again, equations would be helpful for describing how OC burial rates were calculated.**

Response: We now give the equations of these calculations in order to clarify (see also our reply to reviewer #1).

❒ **Line 205: The spatial analysis for pore water CH4 saturation and C:N was done with fewer data points right?**

Response: Yes, we had 25 sites for pore water CH_4 concentration and 19 for C:N ratio. However, the interpolation of pore water CH_4 or sediment C:N is only used for visualization, and not used for any quantitative analysis. In order to clarify, we added the sampling sites in the figures, as dots, and we mention in the "Data analysis" section that these interpolations are used for visualization only.

❒ **Lines 206-212: I'm unclear how the land cover data was used in this paper.**

Response: The land cover analysis was indeed underexplored in our manuscript. We now added more information on how we used land cover and on the results we found. We checked if land cover (which is different for the different sub-catchments of the reservoir) has an effect on the spatial distribution of OC burial, CH_4 saturation and C:N ratio. For that, we compared the land cover in the different sub-catchments of the reservoir with the sediment variables along the respective reservoir arm. We found that the arms with higher SAR and OC burial rate, as well as higher C:N ratio were in sub-catchments with higher percentage of managed areas.

❒ **Line 244-246: Why are they likely to receive larger sediment inputs? Higher catchment area: surface area ratios?**

Response: Curuá-Una is likely to receive large sediment inputs not only because of the large catchment area : surface area ratio (as of most hydroelectric reservoirs), but also because of the high percentage of forest that contributes with a large input of terrestrial carbon. Moreover, the managed areas in the watershed contribute directly with sediment due to the high vulnerability to erosion.

❒ **Line 288: Get rid of second "in"**

Response: Changed accordingly.

❒ **Line 301-302: See my general comments. This is not convincing as currently written. I think the authors need to show a breakdown of estimated OC burial by latitude or by climate zone to make this point more convincing.**

Response: It was not clear enough in the text that we are comparing in the context of tropical hydroelectric reservoirs. We will clarified this throughout the manuscript.

❒ **Line 331: Change “dominating” to “dominant”**

Response: Changed accordingly.

❒ **Line 334: The lack of a relationship between OC burial rate and C:N ratio is interesting.**

Response: It is indeed. Even though C:N ratio certainly affects OC burial efficiency (and, thus, OC burial rates), the relationship between them is masked by the strong effect of SAR on OC burial. We now discuss this issue more clearly in the revised Discussion.

❒ **Lines 337-339: This seems like a pretty ancillary comment and isn’t very convincing the way currently written/visualized.**

Response: This statement is important to justify the lower C:N ratio in some regions of the reservoirs. We have clarified this in the revised manuscript.

❒ **Line 346: add “for” in btween “accounting” and “the”; Line 347: add “us” in between “allow” and “to”.**

Response: Changed accordingly.

❒ **Lines 375-377: Seems like this information about linkages belongs in the**

introduction.

Response: We use this statement here to give background about our findings, for example, we observed that high burial rates were correlated with a high proportion of samples above the CH_4 saturation, which in turn increases the probability for ebullitive CH_4 emission. We therefore prefer to keep this information.

❒ **Line 383-392 and throughout: It would be helpful to more thoroughly describe to the reader why, in this case, you think the pool of CH4 in the sediment is indicative of the flux out.**

Response: We now more clearly state that a high share of gas bubbles is indicative for an elevated probability of CH_4 ebullition. We do not insinuate that the degree of pore water CH_4 saturation relates quantitative to ebullition flux, because ebullition flux to the atmosphere is also dependent on water depth, grain size, and pressure fluctuations.

❒ **Lines 388-389: Why not just use 100% saturation then? It makes it more comparable to other studies and less confusing.**

Response: We now use 100% as a saturation threshold, and state that because of the high likelihood of gas bubble loss during coring and sampling, the CH_4 concentrations reported are conservative (see also our response to reviewer #1).

❒ **Line 264: I haven't heard to term 'muddy lake area' before. Also, run-of-river reservoirs are probably ones where fine sediment is transported all the way to the dam.**

Response: In CUN, water retention time is low in the main river channel, which is narrow and well separated from the dead tree area, presumably permitting transport of fine sediment to the dam area. We moved the references concerning the term “muddy lake area” to right after the term is mentioned.

❒ Lines 275-276: I thought you used spatial interpolation (not an average)?

Response: The average OC burial from the interpolation (90.9 gC m^{-2} y^{-1}) was practically the same to the average from the coring sites (91 gC m^{-2} y^{-1}). We now use the average from the interpolation and we changed the text accordingly.

❒ Figures 1, 2, and 4: I find the picture of the houses are awkward and I don’t think they really add much to the figure.

Response: The houses are used for interpretation of spatial patterns, thus we prefer to keep them in the graph. However, we changed the picture of the houses and we hope you like it better.

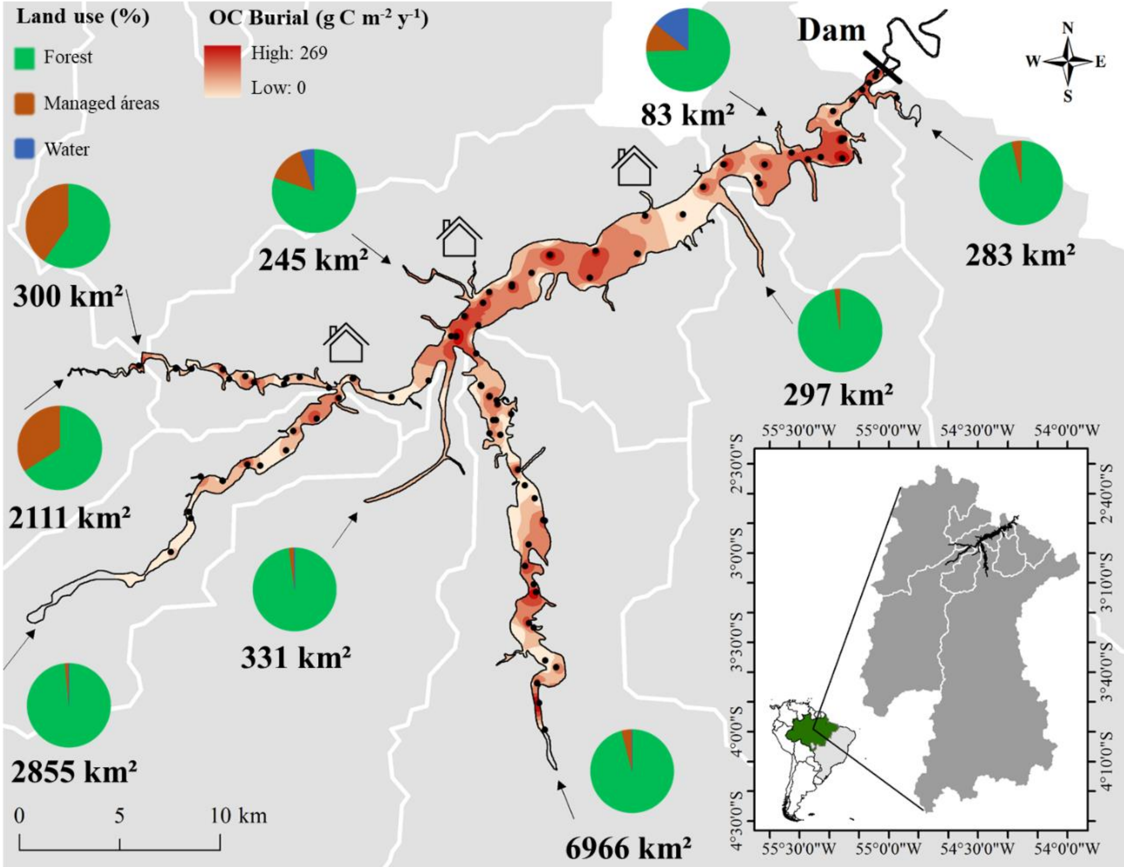

Figure 1. Organic Carbon Burial rate (OC burial; g C m^{-2} yr^{-1}) and land cover of Curuá-Una reservoir. The circles show the land cover of each sub-catchment. The numbers near the circles show the area in km² for each sub-catchment. The black dots represent the sediment sampling sites to estimate SAR and OC burial rates. The arrows represent the main rivers inflow. The house represents settlements at the reservoir. The bottom-right map shows the location of the reservoir in Brazil (the green area is the Brazilian Amazon region) and the total extension of each sub-catchment.

High organic carbon burial but high potential for methane ebullition in the sediments of an Amazonian hydroelectric reservoir

Gabrielle R. Quadra[1]✉, Sebastian Sobek[2], José R. Paranaíba[1], Anastasija Isidorova[2], Fábio Roland[1], Roseilson do Vale[3], Raquel Mendonça[1]

[1] Laboratório de Ecologia Aquática, Programa de Pós-Graduação em Ecologia, Universidade Federal de Juiz de Fora, 36036 900, Brazil.

[2] Department of Ecology and Genetics, Limnology, Uppsala University, 752 36, Sweden.

[3] Universidade Federal do Oeste do Pará, Instituto de Engenharia e Geociências, 68040 255, Brazil.

✉gabrielle.quadra@ecologia.ufjf.br

Abstract

Reservoir sediments sequester significant amounts of organic carbon (OC), but at the same time, high amounts of methane (CH_4) can be produced and **emitted** during **the** degradation of sediment OC. **While the greenhouse gases emission of reservoirs has received quite some attention, there is a lack of studies focusing on OC burial. In particular, there are no studies on reservoir OC burial in the Amazon, even though hydropower is expanding in the basin.** Here we present results from the first investigation of OC burial and CH_4 concentrations in the sediments of an Amazonian **hydroelectric** reservoir. We performed sub-bottom profiling, sediment coring and sediment pore water analysis in the Curuá-Una reservoir (Amazon, Brazil) during rising and falling water periods. A **spatially resolved** mean sediment accumulation rate of 0.6 cm yr^{-1} and a mean OC burial rate of 91 g C m^{-2} yr^{-1} were found. **This** is the highest OC burial rate on record for low-latitude **hydroelectric** reservoirs, probably resulting from high OC deposition onto the sediment compensating for high OC mineralization at 28-30°C water temperature. Elevated OC burial was found near the dam, and close to major river inflow areas. C:N ratios between 10.3 and 17 (mean ± SD: 12.9 ± 2.1) **suggest** that both land-derived and aquatic OC accumulate in CUN sediments. About **23**% of the sediment pore water samples had dissolved CH_4 **above** to saturation concentration, a higher share than **in** other hydroelectric reservoirs, indicating a high potential for CH_4 ebullition, particularly in river inflow areas.

Keywords: Amazon, carbon cycling, C:N ratio, dam, pore water, river inflow

Introduction

Although freshwater ecosystems represent a small fraction of the global area (~4% of terrestrial area) (Downing et al., 2012; Verpoorter et al., 2014), they play an important role in the global carbon cycle, emitting and burying carbon during transport from land to the oceans (Cole et al., 2007; Tranvik et al., 2009). Many studies have been conducted on inland water carbon emissions, while the organic carbon (OC) burial in inland water sediments is comparatively understudied (Raymond et al., 2013; Mendonça et al., 2017). Since a part of the buried OC may offset a share of greenhouse gas emission, it is essential to include OC burial **in the** carbon balance of inland water ecosystems (Kortelainen et al., 2013; Mendonça et al., 2017).

Freshwater OC burial rate varies both in space and time due to many factors, such as land cover, hydrological conditions, OC and nutrient input and climate change (Radbourne et al., 2017; **Stratton et al., 2019**). Several studies have shown that reservoirs bury more OC per unit area than lakes, rivers and oceans (Mulholland and Elwood, 1982; Mendonça et al., 2017), which may be attributed to the high sedimentation rate caused by the extensive sediment trapping when water flow is dammed (Vörösmarty et al., 2003). Considering the importance of reservoirs as a carbon sink (~40% of total inland water OC burial; Mendonça et al., 2017) and the increasing number of hydroelectric dams (Zarfl et al., 2015), the limited number of studies on OC burial in reservoirs severely hampers the understanding of this important component in the carbon balance of the continents (Mendonça et al., 2017). **In particular, large regions of the Earth are at present completely unsampled concerning inland water carbon burial. Approximately 90% of the sites sampled for carbon burial are in North America and Europe, while there are only few**

measurements in South American, African and Asian countries (Mendonça et al., 2017).

To the best of our knowledge, OC burial has so far not been studied in an Amazonian reservoir. However, temperature and runoff were identified as important drivers of OC burial in lakes and reservoirs (Mendonça et al., 2017), and OC burial in Amazonian floodplain lakes was reported to be much higher than in other lakes (Sanders et al., 2017). These observations suggest that **hydroelectric** reservoirs in the Amazon area may bury OC at a comparatively high rate. Moreover, many new hydropower dams are planned in the Amazon due to the high potential of the area for hydroelectricity (da Silva Soito and Freitas, 2011; Winemiller et al., 2016). However, there is currently no data to gauge the potential effect of hydropower expansion in the Amazon on carbon burial.

On the other hand, it has been shown that reservoirs can be strong sources of methane (CH_4) to the atmosphere (Deemer et al., 2016). Several studies have shown a positive relationship between CH_4 production and temperature in freshwater ecosystems (Marotta et al., 2014; Wik et al., 2014; Yvon-Durocher et al., 2014; DelSontro et al., 2016; Aben et al., 2017), and also organic matter supply to sediment is an important regulator **of** CH_4 production and emission (Sobek et al., 2012; Grasset et al., 2018). Thus, tropical reservoirs, especially those situated in highly productive humid tropical biomes, such as the Amazon, may produce more CH_4 than temperate ones due to higher annual temperatures and availability of organic matter in their sediments (Barros et al., 2011; Mendonça et al., 2012; Fearnside and Pueyo, 2012; Almeida et al., 2013), even if highly-emitting reservoirs can also be situated in temperate regions (Deemer et al., 2016). **Further, in many reservoirs, CH_4 ebullition (i.e., emission of gas bubbles) is an important or dominant emission pathway, but it is very difficult to measure due**

to its strong variability in space and time (McGinnis et al., 2006; Deemer et al., 2016). Measurements of dissolved CH_4 concentration in sediment pore water may, therefore, help to identify if ebullition is likely to occur (CH_4 concentrations close to the sediment saturation), and thus to judge if the sediments act mainly as carbon sinks, or also **as** CH_4 sources.

Since both OC burial and CH_4 production take place in sediments **and** may potentially be high in reservoirs in the Amazon area, we conducted a study on the sediments of an Amazonian **hydroelectric** reservoir during hydrologically different seasons. **Here we present the first spatially resolved OC burial estimate and mapping of CH_4 concentrations in sediment pore water in an Amazonian hydroelectric reservoir.**

Material and methods

Study area

Curuá-Una is an Amazonian reservoir (CUN; 2°50′ S 54°18′ W) located in the Pará state (North of Brazil), created in 1977, and used mainly to produce energy. The mean water depth of CUN is 6 m (Fearnside, 2005; Paranaíba et al., 2018) and it has a maximum flooded area of 72 km^2 (Duchemin et al., 2000; Fearnside, 2005). The main tributary is the Curuá-Una River, contributing with most of **the reservoir's** water discharge (57.4%), but rivers Moju (11.7%), Mojuí (4.4%), Poraquê (3.2%) and other small ones (2.9%) are also important (Fearnside, 2005). The catchments of the largest tributaries, entering from the south, consist mainly of tropical rainforest, while the northwestern tributaries also contain a fraction (up to 41%) of managed land **(Fig. 1)**.

The reservoir is characterized by a high amount of flooded dead trees (**area with trees covers** 90% of the total reservoir area), which may be expected to decrease water flow and promote sedimentation. According to a previous study (Paranaíba et al., 2018), CUN is oligotrophic (total nitrogen: 0.7 mg L^{-1}; total phosphorus: 0.02 mg L^{-1}), the surface water is warm (30.1 ± 1.4 °C), slightly acidic (pH of 6.1 ± 0.7), with low conductivity (16 ± 11 µS cm^{-1}) and moderately oxygenated (6.7 ± 1.9 mg L^{-1}).

Sampling

We carried out two samplings in the CUN reservoir. In February 2016, during the rising water period (**Fig. S1**), we used an Innomar SES-2000 parametric sub-bottom profiler operating at 100 kHz (primary frequency) and 15 kHz (secondary frequency) to determine the bathymetry and sediment thickness (**from which we planned to acquire spatially resolved sediment accumulation rates and OC burial rate**, similar to Mendonça et al. 2014). Sediment thickness was difficult to observe **with the sub-bottom profiler**, though, presumably because of the widespread presence of gas bubbles in the sediment which reflect the sound waves very efficiently, preventing them from reaching the sub-bottom layer. Therefore, OC burial rates were determined from sediment cores only. In September 2017, during the falling water period (**Fig. S1**), additional sediment cores were then taken to cover the reservoir as much as possible.

We took a total of 114 sediment cores during the two sampling occasions, **approximately evenly distributed along the reservoir, both longitudinally and laterally,** to **measure sediment thickness and, thus,** estimate **sediment accumulation and** OC burial rates (**Fig. 1**, **Table S1**). Cores were retrieved using a gravity corer equipped with a hammer device (UWITEC, Mondsee, Austria) to sample the entire sediment layer, including the pre-flooding material. **The layer of transition between**

post- and pre-flooding material was visually identified. Visual identification is possible because the moment when the reservoir was flooded is the onset of a lacustrine depositional regime, which is characterized by different sediment texture and composition in relation to the pre-flooding soil or fluvial sediment (**Fig. S2**). The thickness of the post-flooding sediment was noted **in all cores and used to calculate sediment accumulation rates (see 'data analysis').** Nineteen sediment cores**, from sites** spread out **evenly** over the reservoir**,** were sliced in 2 cm thick slices and dried at 40 ºC for further laboratory analysis. The samples were weighed before and after drying and the results are, then, expressed in dry weight.

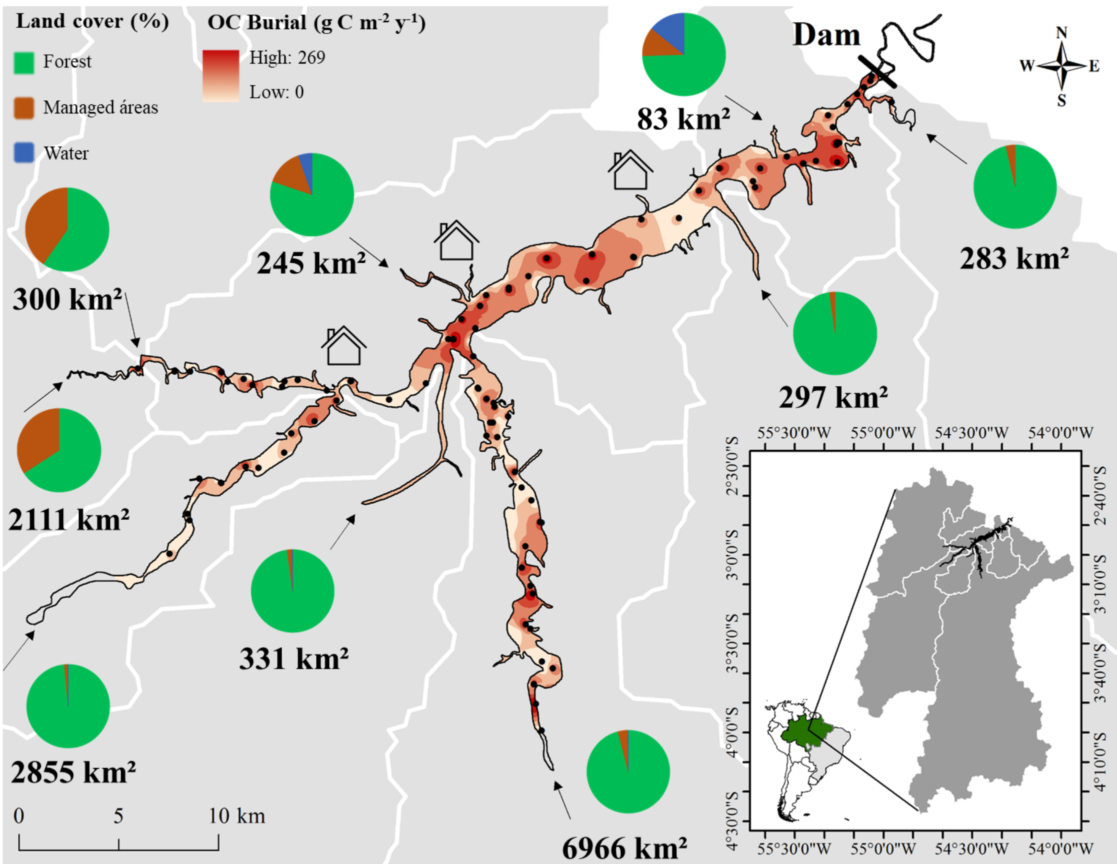

Figure 1. Organic carbon burial rate (OC burial; g C m^{-2} yr^{-1}) of the Curuá-Una reservoir. The circles show the land cover of each sub-catchment**, delineated by white lines**. The numbers near the circles show the area in km² for each sub-catchment. The

black dots represent the sediment sampling sites to estimate OC burial rates. The arrows represent the main river inflows. The houses represent settlements at the reservoir. The bottom-right map shows the location of the reservoir in Brazil (the green area is the Brazilian Amazon region) and the total extension of each sub-catchment.

In both sampling campaigns, cores were taken for the analysis of pore water CH_4 concentration profiles (n = 16 in February 2016 and n = 9 in September 2017). Of the nine cores taken in September 2017, eight were situated at sites previously sampled in February 2016, to compare the CH_4 concentrations between sampling occasions. It is difficult to sample the **exact** same location at different periods due to the water level changes, GPS error and navigation. Thus, the repeated samplings at these eight sites were within < 100 m distance.

Water temperature and dissolved oxygen profiles were measured with a multiparameter sonde (YSI 6600 V2) in a total of 28 depth profiles, distributed across the reservoir at both sampling occasions. Air pressure and temperature were measured with a portable anemometer (Skymaster SpeedTech SM-28, accuracy: 3%), water depth was measured with a depth gauge (Hondex PS-7), and sediment temperature with a thermometer (Incoterm), which was inserted into the sediment right after core retrieval.

Carbon and nitrogen analysis

OC and total nitrogen (TN) concentrations were determined in a sub-set of 19 cores, distributed evenly across the reservoir area. In each of these cores, the first and second layers (0 to 4 cm deep, containing the fresher OC), the last sediment layer above the pre-flooding soil surface (containing the older OC) and one sample every ~8 cm in between (OC of intermediate age) were analyzed. This

selection of layers for C and N analyses was motivated by the exponential decrease of OC mass loss rates during sediment degradation (Middelburg et al., 1993; Gälman et al., 2008). Linear interpolation was used to derive OC and TN concentrations of layers that were not measured.

Dried sediment **samples were** ground in a Planetary Ball Mill (Retsch PM 100) equipped with stainless steel cup and balls. Sediment was packed in pressed tin capsules and analyzed **for TC and TN** with a Costech 4010 elemental analyzer. **The molar C:N ratio in the surface layers was then calculated.** The presence of carbonates was checked in the samples **qualitatively by adding drops of acid and checking visually for reaction. No evidence of solid carbonates was found, thus measurements of TC correspond to OC.**

CH_4 concentration in pore water

The CH_4 concentration in pore water was measured (according to Sobek et al., 2012 and Mendonça et al., 2016) to determine if CH_4 is close to saturation concentration and, thus, prone to form gas bubbles. **The presence of gas bubbles is indicative for an elevated probability of CH_4 ebullition, but not necessarily relates quantitatively to ebullition flux, since ebullition flux to the atmosphere is also dependent on water depth, sediment grain size, and pressure fluctuations (McGinnis et al., 2006; Maeck et al., 2014; Liu et al., 2016).** The top 20 cm (February 2016) or 40 cm (September 2017) of the sediment cores were sampled every 2 cm. Deeper sediment was sampled every 4 cm until the bottom or pre-flooding material. Using a core liner with side ports, 2 ml of sediment were collected using a syringe with a cut-off tip, added to a **25 mL** glass vial with 10 ml of distilled water, and closed with a 10 mm thick butyl rubber stopper. **The slurry (2 mL sediment + 10 mL distilled**

water) was equilibrated with 13 mL headspace of ambient air (void volume of the glass vial) immediately after sampling by vigorously shaking the glass vial, and then the headspace was transferred to another syringe. The headspace was stored in the syringe, closed with a gas-tight valve, and then injected into the analyzer within the same day. The headspace CH_4 concentration was measured by an Ultraportable Greenhouse Gas Analyzer (UGGA, Los Gatos Research) with a custom-made sample injection port, and the peaks were integrated using R software (RStudio Version 1.1.383). The CH_4 concentration in the pore water was calculated from the headspace CH_4 concentration, based on the Henry's law constants. The saturation concentration of CH_4 in **each** sediment **layer** was calculated based on air pressure, water depth, sediment temperature, and sample depth within the sediment core. **The sediment layers with CH_4 concentrations above 100% saturation were considered as prone to ebullition. This is a conservative assumption because it is likely that a part of the CH_4 in the sediment is lost to the atmosphere due to pressure drop during core retrieval, as well as during sample processing.**

Data analysis

The average sediment accumulation rate (SAR; cm yr^{-1}) was calculated for each of the 114 cores by dividing the thickness of the post-flooding sediment by the years since the reservoir construction (39 years in 2016 or 40 years in 2017), according to the equation:

$$Sediment\ accumulation\ rate = \frac{\text{sediment thickness}}{\text{reservoir age}}$$

This approach returns the average sediment accumulation rate over the lifetime of the reservoir (Renwick et al., 2005; Kunz et al., 2011; Mendonça et al., 2014; Quadra et al., 2019), and therefore includes short-term variability in sediment deposition, for example, caused by an episodic change in sediment load or internal sediment movement. The large amount of core samples distributed evenly across the reservoir body also covers the spatial variability in sediment deposition, for example due to sediment focusing (sediment movement with preferential deposition in deeper areas).

OC burial rates (g C m^{-2} yr^{-1}) were calculated for the sub-set of 19 sites where OC content was analyzed. OC mass (g C) in each sediment slice was calculated as OC content (g C g^{-1}) multiplied by dry sediment mass (g). Total OC mass (g C) in the cores was the sum of OC mass in all post-flooding sediment **layers**. Then, **the** OC burial rate (g C m^{-2} yr^{-1}) for each **of these 19 sites was** calculated using the total OC mass (g C), core surface area (2.8 x 10^{-3} m^2) and the reservoir age **at the sampling dates, according to the equation:**

$$Organic\ carbon\ burial\ rate = \frac{\text{Organic carbon mass in the post} - \text{flooding sediment}}{\text{core area} * \text{reservoir age}}$$

SAR was positively correlated to OC burial rate in the sites (see Results; y = 159.03x - 4.4212; R^2 = 0.87; **Fig. S3**), **and we used this regression equation to** estimate the OC burial rate (g C m^{-2} yr^{-1}) for the **remaining 95** coring sites where OC content was not analyzed.

The SAR and OC burial rates from the 114 cores were then interpolated to the reservoir area using the Inverse Distance Weighted algorithm (IDW, cell size of approximately 22 m x 22 m), producing spatially resolved maps of SAR, OC burial rate.

From the spatially-resolved average OC burial rate, the reservoir age (40 years) and total flooded area (72 km^2), we calculated the total OC stock in the reservoir sediment. **Using the same approach, we interpolated the** pore water CH_4 **concentration**, and C:N ratio for the whole reservoir **area**. Spatial analyses were performed in ArcGIS 10.3.1 (ESRI).

In order to investigate any potential relationships between the land cover of sub-catchments and the spatial distribution of sediment characteristics and rates, land cover data was derived from maps of 1 km resolution (Global Land Cover Project, GLC2000), made available by the European Commission's science and knowledge service, including 23 land cover classes. The classes found in the CUN watershed were then grouped in three main classes: (1) forest (tree cover, natural vegetation, shrub, and herbaceous cover); (2) managed areas (cultivated and managed areas, cropland and bare areas); (3) and water bodies. The extent of **the** CUN watershed and sub-catchments were identified using the WWF HydroBASINS tool (HydroSHEDS, 2019).

Results

Water column profiles

The water column temperature profiles showed a mean of 30 ± 1 ºC, 29 ± 1 ºC and 29 ± 2 ºC in the surface, the middle and bottom layer, respectively. The dissolved oxygen average was 7 ± 1 mg L^{-1}, 6 ± 1 mg L^{-1} and 5 ± 1 mg L^{-1} in the surface, the middle and bottom layer, respectively. These water profiles suggest that the relatively shallow water column does not develop stable stratification over any extended periods of time, even if short-lived stratification events can occur (Table S2).

Sediment accumulation and organic carbon burial rates

SAR in the coring sites (n = 114) varied from 0 to 1.7 cm yr^{-1} (mean ± SD of 0.6 ± 0.4 cm yr^{-1}, **Table S1**). In some areas of rocky or sandy bottom, especially near river inflows and along the main river bed, sediment could not be retrieved with our corer and SAR was considered as zero (total of 10 sites). OC burial rate in the coring sites (n = 114) varied from 0 to 269 g C m^{-2} yr^{-1} (mean ± SD of 91 ± 61 g C m^{-1} yr^{-1}, **Table S1**). The highest values of OC burial were observed near the dam, **at the confluence** of **the major** inflowing rivers, and **in** the inflow area of the main tributary, Curuá-Una River (**Fig. 1**). Our sampling was representative of the whole system, from the margins, where there is a greater presence of dead tree trunks, to the river bed, where the sedimentation was **lower** (**Fig. 1**). Therefore, **the simple mean OC burial from the cores resulted in the same** mean OC burial rate derived from **the spatial interpolation (91 g C m^{-1} yr^{-1})**. The **total** burial rate for the CUN reservoir **area** was 6.5 x 10^{10} g C yr^{-1}, corresponding to an accumulation of 0.3 Tg C in CUN sediments since its construction.

C:N ratio and land cover

The C: N ratio of the surface layers **of sediment** (n = 19)**, used as an indicator of organic matter source,** varied from 10.3 to 17 (average ± SD of 12.9 ± 2.1, **Table S3**). Higher C:N ratios were observed in the dam area and at the river inflows (**Fig. 2**). Tropical rain forest is the **dominant** land cover in CUN, covering 90.8% of the watershed, followed by managed areas (8.9%) and water (0.3%) (**Table S4**).

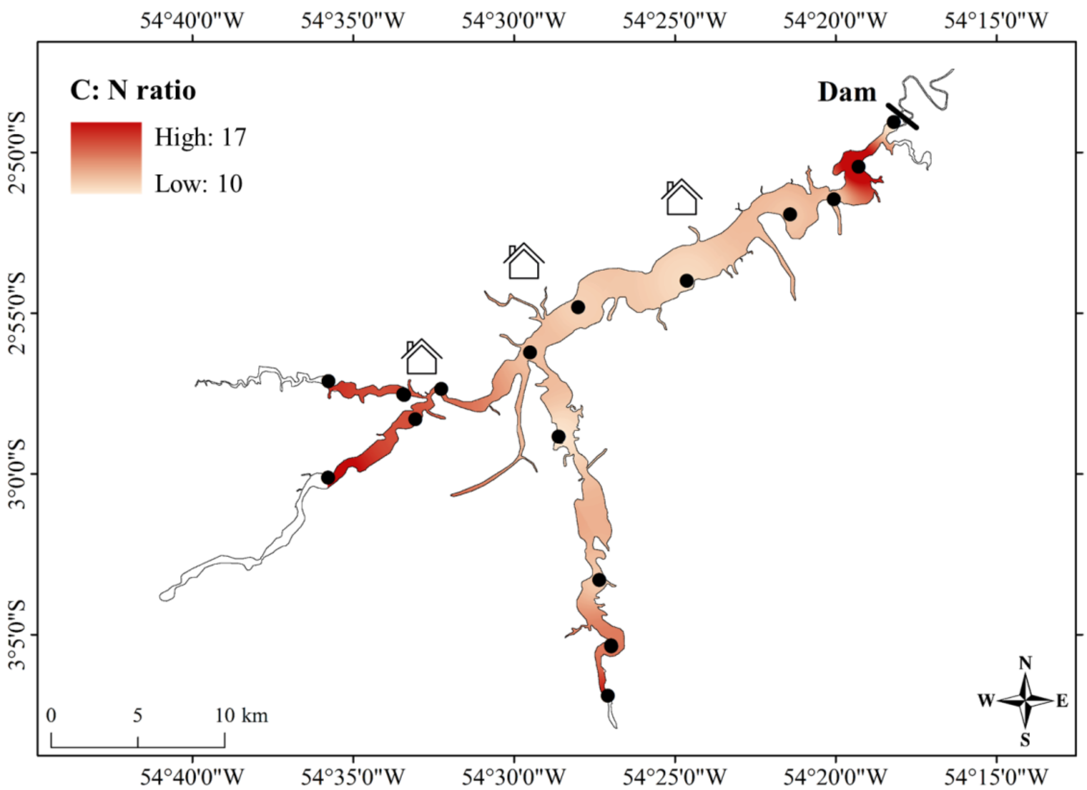

Figure 2. C:N ratio of surface sediment in Curuá-Una reservoir. The black dots represent the sampling sites. The houses represent the settlements at the reservoir.

Pore water CH_4 profiles and saturation

The overall mean CH_4 concentration in pore water from CUN was 1,729 ± 1,939 µM of CH_4 (mean ± SD) with similar averages during rising (1,700 ± 1,637 µM of CH_4, **Fig. S4**) and falling water (1,764 ± 2,243 µM of CH_4, **Fig. S4**) periods. At eight sites, we could make paired observations of CH_4 concentration in sediment pore water at both rising and falling periods (**Fig. 3**). These data show that the seasonal difference of CH_4 concentration in pore water was low and not significant (t-test, $t(14) = -0.08$, $p = 0.94$). **Of the 25 pore water CH_4 profiles, 20 contained at least one sample with pore water CH_4 above the 100% saturation concentration; of the total of 386 pore water samples, 90 samples (23%) were above the CH_4 saturation concentration.** This indicates a **high likelihood** of gas bubble **formation in the majority of the sampled**

sites, and thus the possibility of CH_4 ebullition (**Table S5**). Pore water CH_4 saturation was higher in river inflow areas, especially in sampling sites in the Curuá-Una main river. The confluence of the rivers and the dam **area** were also characterized by high pore water CH_4 (**Fig. 4**). **The widespread appearance of gas bubbles in the sediment is i**n accordance **with the** sub-bottom **profiler** data**, which** for a large part of the reservoir **could** not **be** used **to** identify sub-bottom structures, because of a **very** strong acoustic reflector in surficial sediment, presumably gas bubbles.

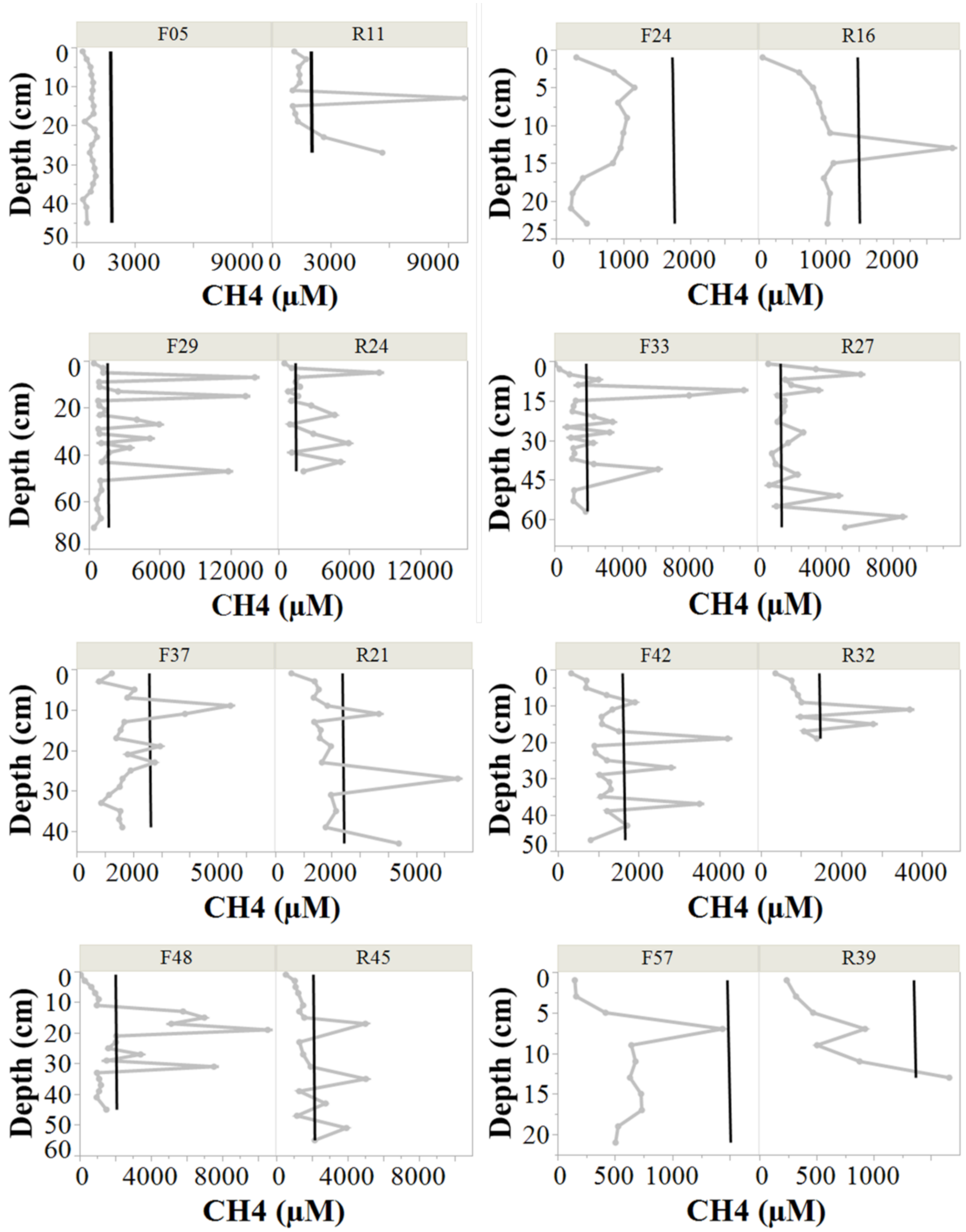

Figure 3. **Paired observations of** pore water CH_4 profiles during rising (R) and falling (F) water periods at eight different sampling sites across the reservoir. Black lines represent the CH_4 saturation line (µM) and grey lines represent the measured CH_4 concentration (µM) over sediment depth.

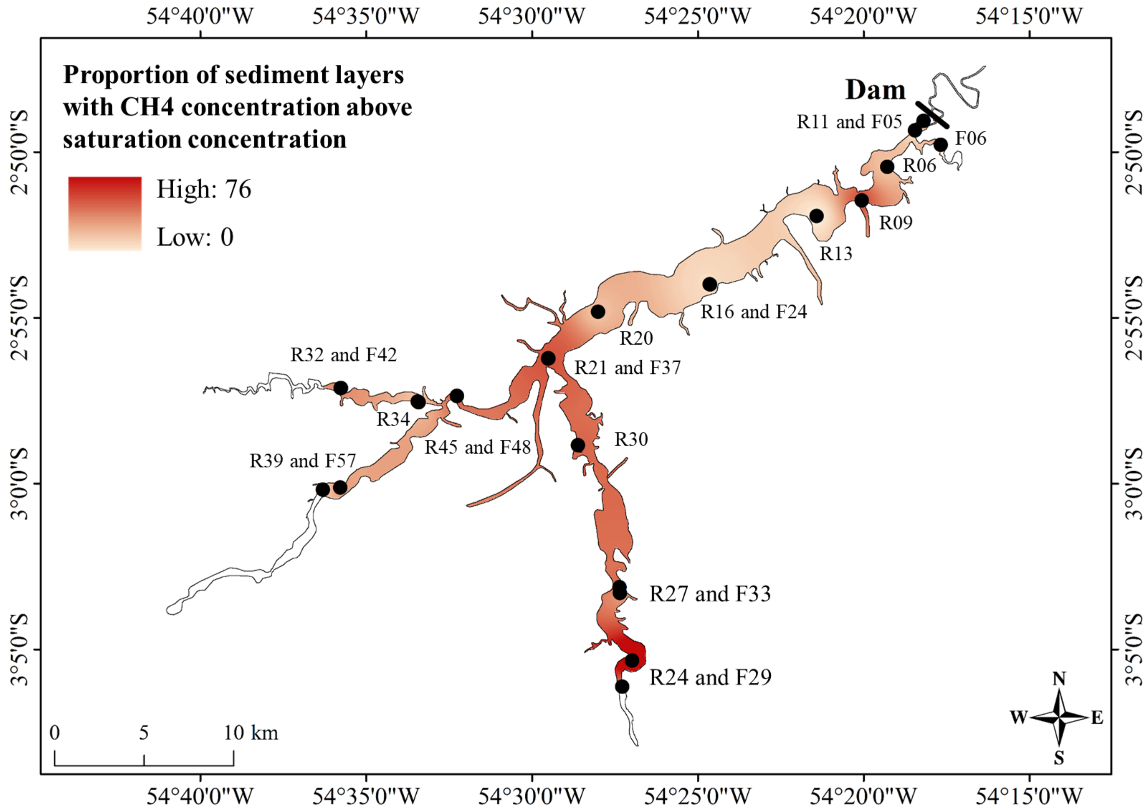

Figure 4. **Percentage of sediment layers with CH_4 concentration above saturation.** The black dots represent the sampling sites to produce the interpolation. The houses represent the settlements at the reservoir.

Discussion

SAR and OC burial in an Amazonian reservoir

When **a** river enters **a** reservoir, the water flow tends to decrease, favoring the deposition of suspended particles (Fisher, 1983; Scully et al., 2003). **Typically,** reservoir **sedimentation rates** are **higher in the inflow areas and lower near the shores (Morris and Fan, 1998; Sedláček et al., 2016).** CUN showed high SAR **near** the inflow areas, especially in the main tributary, but in contrast to other reservoirs (e.g. Mendonça et al., 2014), we did not observe any decrease in SAR towards the margins. **In CUN,** sediment accumulation across the entire reservoir area is favored by the shallow topography of the area, and by the presence of dead tree trunks **along the reservoir including the margins**, which reduce water flow and wave-driven resuspension. Accordingly, our data show that SAR was randomly distributed in relation to the water column depth (**Fig. S5**). Some reservoirs show higher sedimentation rates near the dam, which **can be** called 'muddy lake area' (Morris and Fan, 1998; Sedláček et al., 2016), and **occurs** in reservoirs where the fine sediment is transported all the way to the dam (Morris and Fan, 1998; Jenzer Althaus et al., 2009; Sedláček et al., 2016; Schleiss et al., 2016). CUN may be one of those cases (**Fig. 1**), possibly because water retention time is low in the main river channel which is narrow and well separated from the dead tree area, permitting transport **of fine-grained sediment** until the **deeper** dam area (**Fig. S6**), where sediments tend to accumulate (Lehman, 1975; Blais and Kalff, 1995). **Sediment accumulation was also high at the confluence of the three main tributaries (Fig. 1), probably due to sediment deposition as water flow slows down when the rivers enter the main body of the reservoir.**

Although average SAR **in CUN (0.6 cm yr^{-1}) was only** slightly higher than **that of** non-Amazonian reservoirs in Brazil (**e.g.** Mendonça et al., 2014: 0.5 cm yr^{-1}; Franklin et al., 2016: 0.4 cm yr^{-1}), **OC burial rates were much higher in CUN than in other hydroelectric reservoirs in the tropics and sub-tropics . For example, OC burial was four times lower in Lake Kariba (23 g C m^{-2} yr^{-1}, Zimbabwe, Kunz et al., 2011) and about two times lower in Mascarenhas de Moraes (42 g C m^{-2} yr^{-1}, Brazil, Mendonça et al., 2014) and other Brazilian reservoirs (40 ± 28 g C m^{-2} yr^{-1}, Brazil, Sikar et al., 2009) when compared to CUN. Even though natural lakes tend to bury OC at lower rates than artificial reservoirs (Mendonça et al., 2017), some Amazonian floodplain lakes showed higher OC burial rates than the CUN**

reservoir (266 ± 57 g C m^{-2} yr^{-1}; Sanders et al., 2017). This is probably due to their smaller sizes which may result in a higher SAR since there is little area for sediment deposition, but high sediment load from the river during periods of high discharge. While a comparison with the latest global estimate of OC burial in reservoirs – median of 291 g C m^{-2} yr^{-1} (Mendonça et al., 2017) may lead to the conclusion that OC burial in CUN is low, it must be accounted that this global estimate (Mendonça et al., 2017) includes many small agricultural reservoirs (farm ponds), which are generally highly eutrophic systems that receive high sediment inputs from agriculture, resulting in extremely high OC burial rates (Downing et al., 2008). Hence, if compared to other hydroelectric reservoirs at low latitudes, our conclusion remains that OC burial in CUN is high. Importantly, comparisons of mean SAR and OC burial rate between studies may be complicated by different sampling schemes, as sedimentation can vary in space and time (Radbourne et al., 2017; Stratton et al., 2019); for example, while in some studies, sites along the margins with zero sedimentation were sampled (e.g. Mendonça et al., 2014; our study), in other studies it was not (Moreira-Turcq et al., 2004; Knoll et al., 2014).

The high OC burial in CUN when compared to other low-latitude hydroelectric reservoirs is probably due to the high OC inputs from the productive Amazonian rain forest (Zhang et al., 2017), which compensates the intense sediment mineralization rates caused by high temperature. Using the linear regression model from a compilation of mineralization in freshwater sediments from the literature (OC mineralization = 1.52 + 0.05 x temperature; Cardoso et al., 2014) and the mean temperature of the bottom water in CUN (29°C), sediment OC mineralization is estimated at 325 g C m^{-2} yr^{-1}. This estimate of the sediment mineralization rate is in the upper end of the range of values found for Brazilian

reservoirs (Cardoso et al., 2014), but may even be conservative given that the CUN reservoir is located in a highly productive biome with high organic matter supply. The total OC deposition rate onto the sediment (OC mineralization + OC burial) of CUN is thus 418 g C m^{-2} yr^{-1}, returning a OC burial efficiency of 22 % (OC burial efficiency = OC burial / OC deposition rate; Sobek et al., 2009). As expected, due to the positive effect of temperature on mineralization, the estimated OC burial efficiency in the CUN reservoir is low in comparison to other reservoirs (at least 41% in the tropical lake Kariba (Kunz et al., 2011); mean of 67% in the sub-tropical Mascarenhas de Moraes reservoir (Mendonça et al., 2016); mean of 87% in the temperate lake Wohlen reservoir (Sobek et al., 2012)). A low OC burial efficiency allows high OC burial only if OC deposition onto the sediment is high enough, and we suggest that the high productivity of the surrounding Amazonian rainforest constitutes a strong OC supply to CUN sediments.

The C:N ratio indicates that the sediment OC in CUN consists of a mixture of land-derived and internally-produced OC. The **surface sediment** C:N ratio varied from 10.3 to 17.0 (**Table S3**), and the C:N ratios of phytoplankton are typically 6-9, **of** aquatic macrophytes >10, **of** land plants >40 (Meyers and Ishiwatari, 1993; Grasset et al., 2019) and **of Amazonian topsoils 10 to 14 (Batjes and Dijkshoorn, 1999).** Higher **C:N** values at the river inflow **areas** (**Fig. 2**) may indicate input from the highly productive watershed and thus the high load of land-derived OC to the sediment. **Tropical rain forest is the dominant land cover in the CUN catchment (91%, Table S4), which may suggest that that the high OC burial rates in CUN are related to a high OC input from the watershed. However, probably due to the strong effect of SAR on OC burial, there was no strong relation between OC burial rate and C:N ratio (Fig. S7A),** even **though the C:N ratio has been shown to affect the OC burial**

efficiency (Sobek et al., 2009). In addition, the middle section of the reservoir was characterized by relatively low C:N ratio, indicating a significant share of aquatic OC in the sediment (Fig. 2). Likely, the higher water transparency downstream from the river inflow areas due to particle settling stimulate aquatic primary production. Possibly, also sewage input from riverside communities (represented as houses in Fig. 2) contributes with N to the reservoir and thus further stimulates aquatic production, since a comparatively low C:N ratio was found near these settlements. Also, even at low C:N ratios, OC burial rates were high (**Fig. S6A**). Hence, it is evident that internally-produced OC makes up an important contribution to the OC buried in the sediments of CUN. The source of buried OC has an important implication in terms of accounting for the sediment carbon as a new sink or not (Prairie et al., 2017); however, our data do not allow us to make a quantitative estimate of the share of the CUN sediment carbon stock that is of aquatic origin, and thus may be accountable as a new carbon sink resulting from river damming (Prairie et al., 2017).

The spatial pattern of OC burial suggests that the catchment size affects sediment load and sedimentation, since the largest sub- catchment n (6966 km^2), entering CUN from the south, corresponds with high OC burial rates in the southern river inflow area (Fig. 1). The northwestern tributaries, which drain only 2111 and 300 km^2, are not associated with high OC burial in the northeastern tributary (Fig. 1), possibly because they are smaller, even though they have a higher share of managed land (34 and 41%, respectively) than the southern sub-catchment (4%). Apparently, even though land management is known to increase erosion (Syvitski and Kettner, 2011), we cannot detect any such effect on sediment OC burial. Also concerning the C:N ratio, an effect of land cover is not evident, since the inflow area of the forest-dominated sub-catchment in the southwest (2855

km^2; 99% forest) had a similar C:N ratio as the tributary of the northwestern sub-catchments, with their higher share of managed land. Possibly, the effect of land cover is masked by other factors affecting sediment OC and C:N, such as internal productivity and local particle settling patterns.

Despite being high compared to other hydroelectric reservoirs, OC burial in CUN represents only 15% of the total carbon emission to the atmosphere reported for the CUN reservoir (509 g C m^{-2} yr^{-1}, Duchemin et al., 2000). Similarly, a study conducted in a boreal Canadian reservoir found that OC burial corresponded to 10% of reservoir C emission (Teodoru et al., 2012), although burial in other reservoirs can be close to (70%, Mendonça et al., 2014) or even much higher than the total carbon emission to the atmosphere (1600%, Sobek et al., 2012). The magnitudes of carbon burial in relation to the emission in reservoirs depends on many factors (Mendonça et al., 2012). Therefore, although freshwater carbon emission tends to be consistently higher than OC burial in Amazonian freshwater systems **(Mendonça et al., 2012), we cannot speculate in how far the results of this study applies to other reservoirs in the Amazon region since many factors affect the carbon processing in inland waters.**

High potential for CH_4 ebullition

Sites with higher OC burial rate**, i.e. river inflow areas, especially the Curuá-Una river, the confluence of the three main rivers and the dam area**, also showed a tendency towards higher extent of CH_4 saturation (**Fig. 5**). Hence, the CH_4 production in CUN sediments may rather be driven by the OC supply rate to anaerobic sediment layers than by the reactivity of the sediment OC, **since there was** no association between the C:N ratio and the extent of CH_4 saturation (**Fig. S7B**). Links between high sedimentation rate and sediment CH_4 pore water concentration as well as CH_4 ebullition have been reported previously (Sobek et al., 2012; Maeck et al., 2013), and in addition, fresh land plant-derived organic matter such as leaves **transported by the rivers** may fuel substantial CH_4 production at anoxic conditions (Grasset et al., 2018). This highlights that sediment accumulation bottoms close to river inflow areas can be prone to exhibit high CH_4 ebullition (DelSontro et al., 2011), not least because the shallow water column in inflow areas (**Fig. S6**) facilitates CH_4 bubble transport to the atmosphere.

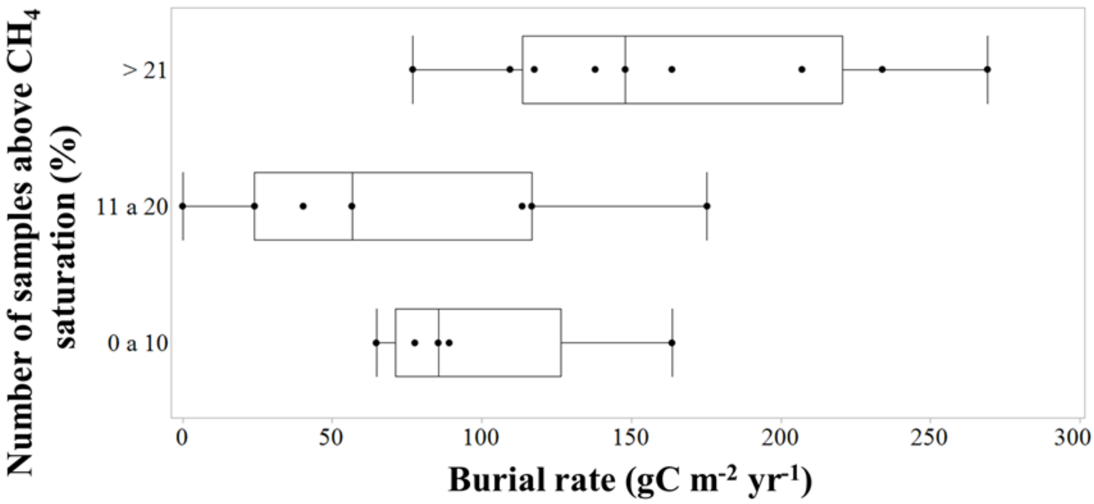

Figure 5. Boxplot of percentage of sediment layers with CH4 concentration above saturation and OC burial rate.

Compared to other reservoirs**, CUN had a higher share of sites (20 of 25) with pore water CH_4 concentration over the saturation threshold.** In **the** Mascarenhas de Morais reservoir (Brazil), 6 of 16 sites with pore water CH_4 concentration over the saturation threshold were found (Mendonça et al., 2016). In Lake Wohlen (Switzerland), 4 of 8 sites with pore water CH_4 concentration over the threshold were found (Sobek et al., 2012). **Using the 100% saturation concentration as a threshold**

may underestimate the potential for ebullition, since changes in the pressure may result in bubbles release during sediment sampling, especially in layers above 100% saturation. Therefore, our results of the degree of pore water CH_4 saturation, as well as the results from the literature cited above, are conservative.

We did not find statistical difference between CH_4 pore water concentration during rising and falling periods (Fig. 3), although other studies suggest a strong influence of water level or pressure changes on CH_4 ebullition (Mattson and Likens, 1990; Eugster et al., 2011; Maeck et al., 2014). Interestingly, 2 of **the** 8 sites with generally low CH_4 pore water concentration were low at both sampling occasions, indicating that there may be an important spatial component in sediment CH_4 production **and saturation** (**Fig. 3**, sites F24 x R16 and F57 x R39), which however was not related to the C:N ratio or OC burial rate at these sites.

Conclusions

The comparatively high OC burial rate of the Amazonian CUN reservoir **probably** results from high OC deposition onto the sediment, since the warm water (28-30°C) implies a high sediment OC mineralization rate. **The forest seems to be a major OC source to the reservoir although** the relatively low C:N ratio in large parts of the reservoir indicates a significant aquatic contribution to sediment OC burial. In some parts of the reservoir, particularly in the river inflow areas, sediments are probably a CH_4 source by ebullition. **Therefore, large inputs from a highly productive forest probably boost the OC burial rate, as well as CH_4 production, with a still unknown net effect.** Given the planned expansion of hydropower dams in the Amazon region, future studies should quantify how OC burial and CH_4 emission may be affected by new Amazonian hydroelectric reservoirs.

Data availability. All the data used in this study can be found in the manuscript and in the Supplement.

Author contributions. GRQ, JRP, AI, RM, RV carried out the sampling campaings. GRQ processed the data. AI analyzed the samples. GRQ and JRP prepared the figures. RM, SS, FR designed the study. All authors contributed to interpreting data and writing the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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