

Author's response to comments from anonymous referee #1

We would like to thank the referee for his/her thorough examination of the manuscript and his/her constructive comments which were used to clarify and improve the manuscript as reported here.

This study is significant in that it attempts to determine the relative importance of various sources of CO₂ and CH₄ to evasive fluxes from a reservoir. The authors have identified four main sources (lotic inflow, hypolimnion, sediments, water column metabolism) and upscaled measurements and models of these fluxes to determine relative importance to the epilimnion. They find that there is a missing source of CO₂ to both the branches and the main basin and a missing source of CH₄ to the main basin. I think it's an interesting result that the model can't be closed, but it deserves more attention, perhaps in the title and the abstract. This work falls within the scope of Biogeosciences and generally scientifically sound, with a few exceptions.

We thank the referee for acknowledging the scope and significance of this research.

My main concern is with the handling of metabolism, and therefore the accuracy of the title and one of the key findings. The authors measure production of CO₂ via aerobic metabolism with two methods: bottle incubations and single-station DO measurements. Additionally, the authors measure the metabolic production of CH₄ with bottle incubations, which is an interesting and important aspect of this study. However, these metabolism measures are the most uncertain component of their model. The two methods for metabolic CO₂ production disagree in sign and by an order of magnitude. And, the results for metabolic CH₄ production are highly uncertain with the SE greater than the mean. I think all the authors can conclude is that their estimates for metabolism are highly uncertain and that metabolism has the potential to close the model because the other fluxes are relatively well constrained. Yet the title (Sources and processes sustaining surface CO₂ and CH₄ fluxes in a tropical reservoir: the importance of water column metabolism) makes it sound like the main finding is that metabolism is the most important source. Additionally, the abstract says, "internal water metabolism remains a dominant driver". I wish that the discussion of this missing sources (like in lines 455-459 of the discussion) was more straightforward in the title, abstract, and results section.

This point was raised by the two reviewers, and following their feedback we do agree that the wording used in the interpretation of the results on metabolism and its relative importance were confusing and inadequate in some instances. In this regard, we have made major changes to the new version of the manuscript aiming at better presenting the role of metabolism and shifting the main message to the overall gas budgets. Changes were made throughout the manuscript as follows:

Title: *"Changing sources and processes sustaining surface CO₂ and CH₄ fluxes along a tropical river to reservoir system"*

Abstract (L.16 - 20): *"Water column metabolism exhibited wide amplitude and range for both gases, making it a highly variable component, but with a large potential to influence surface GHG budgets in either direction. Overall our results show that sources sustaining surface CO₂ and CH₄ fluxes vary spatially and between the two gases, with internal metabolism acting as a fluctuating but key modulator."*

Results section 3.7.1 (L.356 - 360): *"Including the metabolism substantially shifts the mean of the CO₂ epilimnetic budget (sum of sources and sinks) to a negative value and drastically increases its uncertainty (Fig. 3a, b and Table S2), reflecting a potentially important but poorly resolved role of metabolism in the budget because of its variability. However, given that metabolism acts more likely as a CO₂ sink on average, our best assessment suggests that, vertical transport from deeper layers is the main source sustaining surface CO₂ out-flux in the main basin of Batang Ai."*

Discussion section 4.3 (L.475 - 478): *"When reported as mean areal rates, CH₄ metabolism ranged from net consumption to net production of CH₄ (-0.29 to 0.94 mmol.m⁻².d⁻¹), which reflects its potential in having a high impact, either positive or negative, on the epilimnetic CH₄ budget at the reservoir scale (Fig. 3d and Table S3)."*

Discussion section 4.4 (L.507 - 510): *“The combination of our results suggests that water column metabolism could be the dominant source of CH₄ in the main basin of Batang Ai, potentially sustaining up to 75 % of surface emissions in that reservoir section.”*

Conclusion section 5 (L.418 - 423): *“Nonetheless, the epilimnetic budgets of both gases presented a high sensitivity to water column metabolism. This result is likely representative of large systems with a high volume of water versus sediments, which is common for hydroelectric reservoirs. However, metabolic balances of CO₂ and CH₄ were extremely variable in space and time, switching from a net production to a net consumption of the gases, and leading to highly uncertain ecosystem-scale estimates, which emphasizes the key but unconstrained role of metabolism in the overall GHG budgets.”*

Further, Figure 5, which I would interpret as aerobic metabolism not being a dominant control on CO₂ dynamics, isn't even mentioned in the results section.

The deviation from 1:1 line in Figure 5 shows indeed that metabolism with a quotient of 1 is not the dominant force controlling CO₂ surface concentration which results from several possible factors as explained in the discussion section 4.2. Mentions of metabolism dominance were removed or edited (see previous comment) and Figure 5 was introduced in the result section 3.6.1 (L.330 - 333):

“To complement metabolic rate data, surface O₂ and CO₂ departure from saturation were examined in both reservoir sections. O₂ oversaturation was observed in 44 % of cases in the main basin and 81 % in the branches (Fig. 5), which corresponds with the spatial patterns of net metabolic rates (Fig. 4b). CO₂ oversaturation was also widespread (74 % of cases), making many sampled sites oversaturated in both O₂ and CO₂ (55 % in the branches and 32 % in the main basin, Fig. 5).”

I'm also unclear on which CO₂ metabolism data is presented in Figure 3.

In the new manuscript version the caption of Figure 3 was edited to clarify the metabolism data presented, and we also added a concise method section 2.8 to clarify the purpose and calculations behind Figure 3 (L.240 - 247):

“2.8 Epilimnetic GHG budgets

Areal rates of horizontal, vertical, sediment, and metabolic inputs were combined into a sum of sources / sinks and compared to the rate of surface gas flux for each gas in each reservoir section. A mean and standard error were calculated for every component of the budgets based on measurements averaged across sites and / or sampling campaigns in order to obtain ecosystem-scale estimates of the components means and uncertainties. In the case of CO₂ metabolism, the ecosystem-scale average was calculated as the mean of the two average values derived from the incubation and diel O₂ monitoring methods. For every component, density curves were derived considering a normal distribution based on the mean and its standard error in order to visualize the relative magnitude and uncertainty of each ecosystem-scale areal rate (Fig. 3).”

I'd still like to see a visual more clearly breaking down the relative importance of each source. For example, the abstract says that lotic inflows are responsible for 18%- 100% of CO₂ and CH₄ evasion from the branches. I'm having a hard time making that conclusion from the rest of the paper. For example, the SI table shows that on average 4.3 mmol m⁻² d⁻¹ of total CO₂ flux from the branches (4.7 mmol m⁻² d⁻¹) comes from inflows, which would mean that 91% of CO₂ evasion is sourced from riverine inputs. If the authors are referring to individual samplings, then inflow is between 204% and 18% of CO₂ evasion. Fig 3 doesn't clarify things for me either because I find the color gradient confusing. Inflows are colored as 60% to 150+% of CO₂ evasion, while evasion itself is colored as <-50% to >150% of evasive CO₂ fluxes.

We agree that based on the previous version of Figure 3, the relative importance of each source was not clearly visually presented and the colored % axis was confusing given its large span (from negative to >100 %). Thus we redesigned Figure 3 which now clearly states the values of mean % contribution from each source. To avoid confusion, we marked <0% for negative areal rates instead of assigning them a negative percent contribution. Also, % contribution are now associated only to the mean of the normal distributions rather than considering the whole uncertainty range, which avoids having large ranges in % and focuses on the average contribution for each component. The range of 18-100% referred to the different sampling campaigns, but we agree that it is confusing and replaced it by the mean (>90%) in the corresponding abstract sentence (L.12 - 14):

“Results showed that horizontal inputs are an important source of both CO₂ and CH₄ (> 90 % of surface emissions) in the upstream reservoir branches.”

Minor comments related to scientific content:

- Should terrestrial inputs (like soil water) be considered another source? Also, because sediment cores couldn't be taken in the littoral zone, it seems like there might be a missing source or two (terrestrial inputs, littoral zone) from the model. I do appreciate that the authors discuss that their sediment fluxes might be higher than the average. Is it justified to assume that water inflow is equal to water outflow of the reservoir? While soil water inputs (and other lateral flow) were not measured, they were implicitly accounted for as horizontal inputs by considering a steady state where the total amount of inflowing water to the reservoir equals the outflow at the dam. While this assumption is likely a simplification of reality, it seems like the best approach given the limited available data on the hydrography of the system. However, the questions of the referee on this point are very pertinent, thus we edited the method section 2.4 to better explain the choice of this approach, its assumptions, and its limitations (L.124 - 133):

“In order to estimate the external horizontal inputs of CO₂ and CH₄, we considered that the total volume of water inflow and outflow (discharge measured at the dam) were equal, and equivalent to the mean of measured daily discharge (Q , in $m^3 d^{-1}$) during each campaign (considering minimal changes in inflow / outflow rates during a campaign). The approach of using discharge as a measure of total water inflow has the advantage of integrating all external flow (rivers, lateral soils, and groundwater) as water inputs to the reservoir. However, the fraction of inflow feeding the reservoir surface versus bottom layer, and its average gas concentration can only be approximated based on measurements from the two main river inlets (Fig. 1) due to the lack of data on other lateral inflows. Given that part of the inflowing water is colder and denser than the reservoir surface layer, only a fraction of it enters the epilimnion of the reservoir branches, and the rest plunges into the hypolimnion. We estimated that fraction (f_{epi}) based on temperature profiles in the East river delta and branch (sites P1 and P2, Fig. 1), and assumed it is representative of other water inflows to the reservoir.”

- I don't agree with the statement that the two methods for CO₂ metabolism “match fairly well” (line 311). We agree with the referee that this is an incorrect formulation, we rephrased that sentence as follows (L.325 - 326):
“In the main basin, incubation results ranged from -8.8 to 7.2 $\mu\text{mol L}^{-1} d^{-1}$, while the diel O₂ technique captured a wider variability in net CO₂ metabolic rates from -19.2 to 6.1 $\mu\text{mol L}^{-1} d^{-1}$ ”
- Line 332 doesn't match the data presented in Table S2. Horizontal inputs are in general an order of magnitude greater than vertical inputs, not in the same range.
The statement was removed.
- The finding presented in lines 399-400 of the discussion section is not presented in the results section.
A sentence was added in the result section 3.6.1 (L.322 -323):
“Daily metabolic rates showed no correlation with mean daily rain or light (Kendall rank correlation p -value > 0.1).”
A statement was added in the method section 2.7 for the collection of light data (L.210 - 211):
“...along with light sensors (model HOBO Pendant from Onset).”
- Lines 411-415 belong in the results section
These sentences were edited and moved to the result section 3.6.1 (L.330 - 333):

“To complement the metabolic rate data, surface O₂ and CO₂ departure from saturation were examined in both reservoir sections. O₂ oversaturation was observed in 44 % of cases in the main basin and 81 % in the branches (Fig. 5), which corresponds with the spatial patterns of net metabolic rates (Fig. 4b). CO₂ oversaturation was also widespread (74 % of cases), making many sampled sites oversaturated in both O₂ and CO₂ (55 % in the branches and 32 % in the main basin, Fig. 5).”

The discussion section 4.2 was also edited accordingly (L.443 - 445):

“Additionally, surface O₂ versus CO₂ concentrations shows that the departure of these gases from saturation varies widely around the expected 1:-1 line, with many surface samples oversaturated in both O₂ and CO₂, especially in the branches (Fig. 5).”

- Figure 6 is not presented in the results section

Description of the results in Figure 6 were added to section 3.2 (L.270 - 274):

“In the main basin surface CH₄ concentration significantly decreased with distance to shore in Nov-Dec 2016 ($R^2_{adj} = 0.54$, p -value < 0.001), but this correlation was weaker ($R^2_{adj} \leq 0.13$, p -value ≥ 0.03) during other sampling campaigns (Fig 6a). Surface $\delta^{13}CH_4$ values varied widely, between -83.3 and -47.6 ‰, but did not show a consistent spatial pattern (Fig. 2f) apart from a positive correlation with distance to shore in the main basin in Nov-Dec 2016 ($R^2_{adj} = 0.29$, p -value = 0.01, Fig. 6b).”

- Figure S2 – linear regression lines shouldn't be drawn if the relationship is insignificant

We understand the referee's point here, although from our perspective the regression lines in Figure S2 are not used to represent the significance of the regressions (based on an arbitrary threshold) but rather as a visual representation of the different slopes reflecting the structure of the data spatially. Thus, we argue for keeping the regression lines regardless of significance, but we are willing to reconsider if this is deemed problematic.

Additional line-by-line comments:

- Line 7 – the qualifier “two potent GHGs” should be directly after the mention of the gases
Fixed (L.7)
- Line 10 – replace “processes” with “sources”
Fixed (L.9)
- Line 35 – remove “, especially”
Fixed (L.35)
- Line 47 – “associated to highly” should be “associated with highly”
Fixed (L.45)
- Line 49 – I'm not sure that I agree with the idea that GPP and ER are often studied separately. The papers that I read tend to report both. Is there a citation you can use to back up this statement?
The sentence was edited and the statement removed (L.47 - 49).
- Line 56 – “lakes” should be “lake”
Fixed (L.55)
- Line 95 – “in 9 sites” should be “at nine sites”
Fixed (L.94)
- Line 105 (and elsewhere) – “Soued et Prairie” should be “Soued and Prairie” or “Soued & Prairie”
Fixed throughout the manuscript.
- Line 136 – “inputs form the” should be “inputs from the”
Fixed (L.137)
- Line 166 – “6-cm-wide” liner
Fixed (L.168)
- Line 255 – The placement of the per mille enrichment range is misleading . . . It currently reads as if the range is the $\delta^{13}CO_2$ value
Fixed (L.266)

- Line 258 – The R² value doesn't match the information in the table
The R² value refers to the linear regression in Figure S1 while Table S1 presents the Kendall correlation coefficient and is cited here for comparison of the link between CH₄ and parameters other than TN.
- Line 267 – The values don't match the tables
One of the value was rounded at the first rather than the second decimal causing the mismatch, this was fixed (L.281).
- Line 272 – “were” should be “was”
Fixed (L.286)
- Figure S3 – I would expect the legend to introduce the plots in order
Fixed
- Line 367 – This citation only applies to CO₂
Citations associated to CH₄ and to lakes and reservoir systems were added (L.386 - 389):
“All these results concord with the a progressively reduced influence of direct GHG catchment inputs and greater preponderance of internal processes along the hydrological flow continuum as observed in river networks (Hotchkiss et al., 2015) and in lakes and reservoirs (Chmiel et al., 2020; Loken et al., 2019; Paranaíba et al., 2018; Pasche et al., 2019).”
- Line 382 – remove “surface”
Fixed (L.405)

Author's response to comments from anonymous referee #3

We would like to thank referee #3 for taking the time to provide constructive comments, essential to increase the clarity and quality of the manuscript. We have modified the manuscript accordingly as described here.

This study is novel as it explicitly parses out evasion of CO₂ and CH₄ (sourced horizontally, vertically, from internal metabolism, and from sediments) from different hydromorphologic parts of a reservoir and its inflows. The results are interesting as well, showing that the CO₂ and CH₄ fluxes fundamentally change along a “river to reservoir continuum” and that the overall reservoir budget cannot be closed. I think this is all very interesting, however I have some concerns (not dissimilar from Referee #1) about the discussion not sufficiently exploring certain results and the title of the paper being misleading. Overall, this work falls under the scope of Biogeosciences and appears to be scientifically sound.

We thank referee #3 for his recognition of the research novelty.

Perhaps most importantly, the manuscripts' title and abstract arrive at (in my opinion) different conclusions than the conclusion of the manuscript. The manuscript's conclusion does not suggest that the primary finding is ‘internal water metabolism remains a dominant driver’ as stated in the abstract. Rather, I read the conclusion's primary finding as an “integrative portrait of the relative contribution of different sources to surface CO₂ and CH₄ fluxes in a permanently stratified reservoir including its transition zones (branches).” I agree with Referee #1 that the massive uncertainties of the metabolism budgets limit the authors' abilities to conclude much from the metabolism values (including its presence in the manuscript's title). I would further argue that this concluding statement is not presented as the main focus of the manuscript's results. The authors allude to the relative contributions of different gas sources in sections 3.3-3.6 but never actually present these relative values. As far as I can tell, they only report the raw fluxes. I suggest the authors focus their statements only on what is directly supported by the results presented in the manuscript, and/or make their presentation of results clearer. I might further add to the results/discussion to sufficiently explore what is being declared in the paper's title, abstract, and conclusion.

This point was raised by the two reviewers, and following their feedback we do agree that the wording used in the interpretation of the results on metabolism and its relative importance were confusing and inadequate in some instances. In this regard, we have made major changes to the new version of the manuscript aiming at better presenting the role of metabolism and shifting the main message to the overall gas budgets. Changes were made throughout the manuscript as follows:

Title: “*Changing sources and processes sustaining surface CO₂ and CH₄ fluxes along a tropical river to reservoir system*”

Abstract (L.16 - 20): “*Water column metabolism exhibited wide amplitude and range for both gases, making it a highly variable component, but with a large potential to influence surface GHG budgets in either direction. Overall our results show that sources sustaining surface CO₂ and CH₄ fluxes vary spatially and between the two gases, with internal metabolism acting as a fluctuating but key modulator.*”

Results section 3.7.1 (L.356 - 360): “*Including the metabolism substantially shifts the mean of the CO₂ epilimnetic budget (sum of sources and sinks) to a negative value and drastically increases its uncertainty (Fig. 3a, b and Table S2), reflecting a potentially important but poorly resolved role of metabolism in the budget because of its variability. However, given that metabolism acts more likely as a CO₂ sink on average, our best assessment suggests that, vertical transport from deeper layers is the main source sustaining surface CO₂ out-flux in the main basin of Batang Ai.*”

Discussion section 4.3 (L.475 - 478): “*When reported as mean areal rates, CH₄ metabolism ranged from net consumption to net production of CH₄ (-0.29 to 0.94 mmol.m⁻².d⁻¹), which reflects its potential in having a high impact, either positive or negative, on the epilimnetic CH₄ budget at the reservoir scale (Fig. 3d and Table S3).*”

Discussion section 4.4 (L.507 - 510): *“The combination of our results suggests that water column metabolism could be the dominant source of CH₄ in the main basin of Batang Ai, potentially sustaining up to 75 % of surface emissions in that reservoir section.”*

Conclusion section 5 (L.418 - 423): *“Nonetheless, the epilimnetic budgets of both gases presented a high sensitivity to water column metabolism. This result is likely representative of large systems with a high volume of water versus sediments, which is common for hydroelectric reservoirs. However, metabolic balances of CO₂ and CH₄ were extremely variable in space and time, switching from a net production to a net consumption of the gases, and leading to highly uncertain ecosystem-scale estimates, which emphasizes the key but unconstrained role of metabolism in the overall GHG budgets.”*

Finally, I suggest expanding what is briefly mentioned at line 390-391: relative contributions of sources and processes governing gas concentrations vary with hydromorphology. I think an expanded discussion pertaining to Figure 6, after adding CO₂ to the figure (and contextualizing it with Figure 2), would help tremendously here, as the influence of the reservoir hydrodynamics could be explored more thoroughly. Similarly, the authors would benefit from engaging more with the existing literature on spatiotemporal variability in gas concentrations within large lakes/reservoirs (e.g. Chmiel et al 2020; Natchimuthu et al. 2017 as examples).

We agree with the reviewer on expanding the literature on spatiotemporal variability, and thus included additional references in the text section 4.7 (Chmiel et al., 2020; Loken et al., 2019; Lupon et al., 2019; Natchimuthu et al., 2017; Paranaíba et al., 2018; Rasilo et al., 2017). We also expanded the discussion on the relative contribution of sources along the hydrological continuum by editing the last paragraph of section 4.1 (L.413 - 427):

“The changing relative contribution of sources and processes shaping surface CO₂ and CH₄ concentrations varies with the system hydro-morphology, from the inflows to the main reservoir basin, and lead to a progressive decoupling between the two gases along the continuum (Fig. S2). The observed CO₂ and CH₄ coupling in the inflows and branches is associated to a common catchment source, as previously reported in other systems including soil-water (Lupon et al., 2019), streams (Rasilo et al., 2017), and lake and reservoir inflow areas (Loken et al., 2019; Paranaíba et al., 2018). Indeed, horizontal inputs are the main source of both CO₂ and CH₄ in the upstream reaches of Batang Ai, accounting on average for 91 and 92 % of their respective surface out-flux in the branch section (Fig. 3a, c and Tables S2 and S3). However, when reaching the main basin, driving sources diverge between the two gases, with vertical inputs from the bottom layer supporting on average 60 % of CO₂ compared to 2 % of CH₄ fluxes, while sediment inputs sustained 7 versus 23 % of CO₂ and CH₄ fluxes respectively in that section. This decoupling partly results from the two gases having distinct metabolic pathways: mainly aerobic for CO₂ and anaerobic for CH₄, leading to their sources and sinks being spatially disconnected in the main basin. Consequently, sediments being a mostly anaerobic environment are a more important source of CH₄ relative to CO₂, while the metalimnetic layer being oxic-hypoxic acts as a sink of CH₄ and source of CO₂ via aerobic CH₄ oxidation (Fig. S4). Overall, the spatial patterns reported here highlight the hydrodynamic zonation common in reservoirs and its diverging effect on CO₂ versus CH₄ cycling.”

Concerning Figure 6, we would like to clarify that it represents CH₄ patterns in the main basin only, so it is not meant to explore the effect of hydrodynamic changes throughout the river to reservoir continuum. The aim of this figure is rather to explore evidences of CH₄ production in the lateral sediment versus the water column using distance to shore as a proxy for distance from lateral sediment as a potential CH₄ source. Since lateral sediment are not known as a large source of CO₂ we don't feel that including CO₂ in Figure 6 is appropriate, unless we have misunderstood the idea behind the suggestion of the referee here.

Following is a list of smaller considerations. Line numbers are in parentheses.

- (25) There are many other citations that are relevant here, in addition to DelSontro et al. (2018), which also show inland waters are significant sources of greenhouse gases. I suggest a more thorough reference set.

Also, 'surface inland waters' implies you are also talking about rivers/streams. If so, you need river-specific references as well.

Two references were included here (Bastviken et al., 2011; Raymond et al., 2013), including river systems (L.25).

- (113 & 119) 'Soued et Prairie' should be 'Soued and Prairie'

Fixed throughout the manuscript

- (123-124) The reference provided here (another biogeoscience paper by the authors) caused me great confusion because it suggests that the interpolated data analyzed in this manuscript is already published, despite the writing style of the methods suggesting the opposite. This needs to be clarified by the authors because if any of this data/methods are already published, I think that should be explicitly declared in this manuscript.

We apologize for the confusion. The data on surface gas fluxes is already published and reused in a different context here. This was clarified in the method section 2.3 by adding the sentence (L.115 - 116):

"Surface gas flux data used in this study are described in more details in Soued and Prairie (2020), a previous study on the C footprint of Batang Ai reservoir."

- (Figure 1) I'm not sure I'm convinced that all notable inflow is coming from these two rivers, and this is likely influential when working at the scale of an individual reservoir. I might suggest adding hydrography to Fig 1, or something similar, to show that there aren't really other noteworthy streams/rivers flowing into the reservoir. (126-128) Along with the previous comment, because you are assuming all inflows are only from these two rivers, reservoir Q could be underestimated (as far as mass balance is concerned). I suggest adding a brief clarifying statement if this is the case.

We agree with the referee that the two rivers represent a large part of the inflowing water but most likely not the entire mass of inflowing water. Unfortunately there is no available information on other potential inflows like smaller rivers or groundwater. However, to counter this problem when calculating horizontal inputs, we used total discharge (measured at the dam outflow) as a representative measure of total inflow to the reservoir (rather than using flow measurements from the two rivers). To clarify this, we edited the method section 2.4 as follows (L.124 - 133):

"In order to estimate the external horizontal inputs of CO₂ and CH₄, we considered that the total volume of water inflow and outflow (discharge measured at the dam) were equal, and equivalent to the mean of measured daily discharge (Q, in m³ d⁻¹) during each campaign (considering minimal changes in inflow / outflow rates during a campaign). The approach of using discharge as a measure of total water inflow has the advantage of integrating all external flow (rivers, lateral soils, and groundwater) as water inputs to the reservoir. However, the fraction of inflow feeding the reservoir surface versus bottom layer, and its average gas concentration can only be approximated based on measurements from the two main river inlets (Fig. 1) due to the lack of data on other lateral inflows. Given that part of the inflowing water is colder and denser than the reservoir surface layer, only a fraction of it enters the epilimnion of the reservoir branches, and the rest plunges into the hypolimnion. We estimated that fraction (f_{epi}) based on temperature profiles in the East river delta and branch (sites P1 and P2, Fig. 1), and assumed it is representative of other water inflows to the reservoir."

- (136) 'for m' should be 'from'

Fixed (L.137)

- (134) Should specify you are referring to surface area rather than area

Fixed (L.136)

- (Fig 2) The boxplots are never explained in the main text or caption. Please define these. Also, please include the number of data points composing these boxplots either in the figure or caption.

The boxplot were actually formed by the points in the plots (each boxplot was composed by the 4 points representing each sampling campaigns), so since they were showing redundant information already represented by the points we decided to remove them.

- (Figure 3) There is no explanation of what Figure 3 is actually plotting until section 3.7, after much of the figure's results have been presented. I think this should be mentioned earlier in the manuscript to clarify what is being presented.

In the new manuscript version we added a concise method section 2.8 to clarify the purpose and calculations behind Figure 3 (L.240 - 247):

“2.8 Epilimnetic GHG budgets

Areal rates of horizontal, vertical, sediment, and metabolic inputs were combined into a sum of sources / sinks and compared to the rate of surface gas flux for each gas in each reservoir section. A mean and standard error were calculated for every component of the budgets based on measurements averaged across sites and / or sampling campaigns in order to obtain ecosystem-scale estimates of the components means and uncertainties. In the case of CO₂ metabolism, the ecosystem-scale average was calculated as the mean of the two average values derived from the incubation and diel O₂ monitoring methods. For every component, density curves were derived considering a normal distribution based on the mean and its standard error in order to visualize the relative magnitude and uncertainty of each ecosystem-scale areal rate (Fig. 3).”

- (Figure 3) Y-axes need values (i.e. the densities). X-axes need to be scaled uniformly for each gas. In its current form, it is very difficult to compare branch versus main basin. Similarity, please add subpanel labels and refer to the specific subplot the paper is currently discussing.

Figure 3 was redesigned and X-axes scaled uniformly as suggested. Also, subpanel identification were added in all figures and referred to in the text. Concerning the Y-axis of Figure 3, it is not possible to add a common axis of densities since each normal distribution is on a separate horizontal axis. Though we believe showing densities might not be essential in this case since it would not offer substantial additional information needed to convey the message the Figure presents.

- (220-221) I’m unfamiliar with this R package but just because you can swap the depth term for the mixed layer depth does not mean that the model is physically realistic for a lotic environment. For example, k600 is often associated with different physical processes in lakes versus rivers and thus modeled differently. This needs an explicit consideration in the manuscript, i.e. why is it ok to run a model built for lentic waters in a lotic environment?

We understand the referee’s questioning on this matter thus we added clarifying statement in the method section 2.7 (L.221 - 225):

“Note that even though the package used was originally developed for streams, it is easily transferable to lakes given that the model used (Eq. (8)) is generalized for all water bodies, with the parameter z_{epi} describing the depth of a mixed water column of either a lentic or lotic system, and with the K600 estimate relying only on data fitting to the model and not on system type.”

As mentioned, K₆₀₀ estimates in the model are derived from maximum likelihood fitting of the data to the model rather being modeled by additional variables related to weather or hydrology, making the model independent of system type.

- (337-338) Isn’t this result just a function of the metabolism uncertainty being so high that it fundamentally effects the aggregate budget (‘T’ in Figure 3)? Or am I misunderstanding something? This is in line with my earlier comments pertaining to drawing conclusions from these metabolism values.

We agree with the referee that this statement is misleading and changed it to highlight the potential influence of metabolism rather than its definite role in the budget (L.356 - 360):

“Including the metabolism substantially shifts the mean of the CO₂ epilimnetic budget (sum of sources and sinks) to a negative value and drastically increases its uncertainty (Fig. 3a, b and Table S2), reflecting a potentially important but unresolved role of metabolism in the budget.”

- (367) Do you mean ‘hydrological continuum’? Also, it is worth nothing that Hotchkiss et al. (2015), which is cited here, is explicitly a study on the lentic hydrological continuum, and not reservoirs or lakes or any lotic waterbodies. I suggest a more appropo reference.

This was changed to hydrological continuum which is in fact a more appropriate word. We also added references associated to lotic systems while keeping the original reference deemed pertinent here since it addresses more explicitly the contribution of external versus internal CO₂ to surface flux. The sentence was edited as follows (L.386 - 389):

“All these results concord with the a progressively reduced influence of direct GHG catchment inputs and greater preponderance of internal processes along the hydrological flow continuum as observed in river

networks (Hotchkiss et al., 2015) and in lakes and reservoirs (Chmiel et al. 2020; Loken et al., 2019; Paranaíba et al., 2018; Pasche et al., 2019)."

Changing sources and processes sustaining surface CO₂ and CH₄ fluxes along a tropical river to reservoir system

~~Sources and processes sustaining surface CO₂ and CH₄ fluxes in a tropical reservoir: the importance of water column metabolism~~

5 Cynthia Soued¹, Yves T. Prairie¹

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Abstract. Freshwaters are important emitters of carbon dioxide (CO₂) and methane (CH₄) ~~to the atmosphere~~, two potent greenhouse gases (GHG). While aquatic surface GHG fluxes have been extensively measured, there is much less information about their underlying sources. In lakes and reservoirs, surface GHG can originate from horizontal riverine flow, the hypolimnion, littoral sediments, and water column metabolism. These ~~processes-sources~~ are generally studied separately, leading to a fragmented assessment of their relative role in sustaining CO₂ and CH₄ surface fluxes. In this study, we quantified sources / sinks of CO₂ and CH₄ in the epilimnion along a hydrological continuum in a permanently stratified tropical reservoir (Borneo Island). Results showed that horizontal inputs are an important source of both CO₂ and CH₄ (~~18 to > 90~~100 % of surface emissions) in the upstream reservoir branches. However, this contribution fades along the hydrological continuum, becoming negligible in the main basin of the reservoir, where CO₂ and CH₄ are uncoupled and driven by different processes. In the main basin, vertical CO₂ inputs and sediment CH₄ inputs contributed to on average 60 and 23 % respectively to the surface fluxes of the corresponding gas. Water column metabolism exhibited wide amplitude and range for both gases, making it a highly ~~uncertain~~variable component, but with a large potential to influence surface GHG budgets in either direction. ~~the most influential but uncertain component in the epilimnetic gas budgets~~. Overall our results show that ~~while~~ sources sustaining surface CO₂ and CH₄ fluxes vary spatially and between the two gases, ~~with internal metabolism acting as a fluctuating but key modulator~~, internal water metabolism remains a dominant driver. However, this study also highlights challenges and knowledge gaps related to estimating ecosystem-scale CO₂ and CH₄ metabolism, which hinder aquatic GHG flux predictions.

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1 Introduction

Surface inland waters are globally significant sources of greenhouse gases (GHG) to the atmosphere, namely carbon dioxide (CO₂) and methane (CH₄) (Bastviken et al., 2011; DelSontro et al., 2018a; Raymond et al., 2013). Freshwaters act as both transport vessels for terrestrial carbon (C) and as active biogeochemical processors, making them key sites of GHG exchange

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30 with the atmosphere (Tranvik et al., 2018). The impoundment of rivers for hydropower generation, irrigation, flood control or
other purposes, changes the landscape and its C cycling (Maavara et al., 2017), often resulting in increased aquatic CO₂ and
CH₄ emissions due to the decay of flooded organic matter (Prairie et al., 2018; Venkiteswaran et al., 2013). Globally, reservoirs
are estimated to emit between 0.5 and 2.3 PgCO₂eq yr⁻¹ (Barros et al., 2011; Bastviken et al., 2011; Deemer et al., 2016; St.
Louis et al., 2000), and this number is predicted to increase with a rapid growth of the hydroelectric sector in the upcoming
35 decades (Zarfl et al., 2015). Several studies have focused on quantifying GHG surface diffusion from reservoirs around the
world and have found extremely high variability temporally and spatially (Barros et al., 2011; Deemer et al., 2016), as is found
in natural lakes (DelSontro et al., 2018a; Raymond et al., 2013). However, less research exists on the relative contribution of
the different sources and processes sustaining surface diffusive fluxes and their variability, especially in reservoirs.

GHG sources to surface waters can be both internal and external. The magnitude of allochthonous inputs, namely terrestrial
40 organic and inorganic C, is known to increase with soil-water connectivity (Hotchkiss et al., 2015), and with soil C content
and leaching capacity (Kindler et al., 2011; Li et al., 2017; Monteith et al., 2007). Soil-derived gas inputs are also temporally
variable, generally increasing with discharge, like during storm events (Vachon and del Giorgio, 2014) or rainy seasons (Kim
et al., 2000; Zhang et al., 2019). Terrestrial inputs in the form of organic C can indirectly sustain surface GHG emissions by
fueling lake / reservoir *in situ* organic matter respiration (Karlsson et al., 2007; Pace and Prairie, 2005; Rasilo et al., 2017).

45 The net internal balance between production and consumption processes of CO₂ and CH₄ influence their surface fluxes. For
CO₂, aerobic ecosystem respiration (ER) and gross primary production (GPP) are highly variable in space and time, and
generally a function of temperature, organic C content and nutrients (Hanson et al., 2003; Pace and Prairie, 2005; Prairie et al.,
1989; Solomon et al., 2013). Net heterotrophy (ER > GPP) is mainly associated with systems receiving high external inputs
of organic C (Bogard et al., 2020; Tank et al., 2010; Wilkinson et al., 2016), while net autotrophy (ER < GPP) has been
50 associated ~~to~~ with highly productive nutrient-rich systems (Hanson et al., 2003; Sand-Jensen and Staehr, 2009). However, a
large part of the variability in measured metabolic rates remains unexplained (Bogard et al., 2020; Coloso et al., 2011; Solomon
et al., 2013) ~~and impeding~~ our ability to accurately predict their net balance, ~~is still weak in part because the two processes are
often studied separately~~. Additionally, anaerobic C transformation adds another level of complexity to the C metabolic balance
by decoupling GPP and ER (Bogard and del Giorgio, 2016; Martinsen et al., 2020; Vachon et al., 2020). For instance,
55 acetoclastic methanogenesis can transform organic C to CH₄ instead of CO₂, and hydrogenotrophic methanogenesis converts
CO₂ to CH₄ without producing O₂.

CH₄ is known to be mostly produced in both profundal and littoral sediments, and reach the water surface by vertical or lateral
diffusive processes (Bastviken et al., 2008; DelSontro et al., 2018b; Encinas Fernández et al., 2014; Guérin et al., 2016).
However, there is increasing evidence that CH₄ production in the oxic water column contributes significantly to lakes CH₄
60 emissions (Bižić et al., 2019; Bogard et al., 2014; DelSontro et al., 2018b; Donis et al., 2017; Tang et al., 2014).
Methanogenesis can be counter-balanced by the oxidation of CH₄ to CO₂ mainly in oxic and hypoxic environments (Conrad,
2009; Reis et al., 2020; Thottathil et al., 2019). While several studies have measured rates of CH₄ production and oxidation in
lakes and reservoirs, few have quantified the net balance of these two processes at an ecosystem-scale (Bastviken et al., 2008;

Schmid et al., 2007; Vachon et al., 2019). According to Vachon et al. (2019), this balance is tightly controlled by physical processes within the water column.

Physical mixing in lakes and reservoirs indirectly impacts C metabolic processes by shaping the O₂ profile, and directly affects GHG surface diffusion by controlling the transport of CO₂ and CH₄ from deep to surface water layers (Barrette and Laprise, 2005; Kreling et al., 2014; Pu et al., 2020). Despite its potential importance (Kankaala et al., 2013), very few studies quantified vertical gas transport and the role of this process in fueling surface GHG emissions. The movement of gases within a system depends on the structure of the water column, which changes spatially along the aquatic continuum. Reservoirs in particular exhibit strong gradients in morphometry and hydrology, translating into high spatial heterogeneity in surface GHG fluxes to the atmosphere (Paranaíba et al., 2018; Teodoru et al., 2011).

Understanding what regulates surface CO₂ and CH₄ concentrations and fluxes to the atmosphere requires knowledge of the interplay between all physical and biogeochemical processes involved, and how they vary spatially. While a number of studies have assessed some processes individually or by difference, very few have measured all relevant components of the epilimnetic mass-balance simultaneously. Here we report on a field study in a tropical East Asian hydropower reservoir quantifying external inputs, sediments inputs, net CO₂ and CH₄ metabolism, vertical diffusion from deeper layers and gas exchange at the air-water interface. This allowed us to estimate the relative contribution of each process in shaping surface GHG emissions from the reservoir, and to test whether the epilimnetic mass balance can be closed. The two major rivers feeding the reservoir flow into two elongated branches, acting as a transition zones, before reaching the main basin. This configuration, common in reservoirs, allowed us to quantify and compare epilimnetic CO₂ and CH₄ regulation in two morphometrically different areas (reservoir branches and main basin). Overall, the aim of this study is to provide an ecosystem-scale portrait of the processes sustaining surface CO₂ and CH₄ emissions and examine how they change when transitioning from a river delta to an open basin.

2 Materials and methods

2.1 Site and sampling description

The study was conducted in Batang Ai hydroelectric reservoir in Sarawak Malaysia (latitude 1.16° and longitude 111.9°). The reservoir is located on the Borneo Island in a tropical equatorial climate with a constantly high temperature averaging 23 °C and 32 °C during nighttime and daytime respectively (Sarawak Government, 2019). The region experiences two weak monsoon seasons (November to February and June to October) with a yearly average rainfall of 3300 to 4600 mm (Sarawak Government, 2019). The reservoir was impounded in 1985 with a dam wall of 85 m, a surface area of ~68.4 km² and a watershed area of 1149 km² of mostly undisturbed forested land (limited rural habitations and small scale croplands).

We distinguish between three sections of the study site: inflows, reservoir branches, and reservoir main basin shown in Fig. 1. The inflows are the two main reservoir inlets: Batang Ai and Engkari rivers (3 to 10 m deep where sampled). The two rivers flow into two arms that we refer to as the reservoir branches (10.8 km², mean and max depths of 18 and 52 m respectively).

The reservoir branches merge into the main basin of the reservoir (58.9 km², mean and max depths of 30 and 73 m respectively). Surface sampling was performed in 36 sites across the three study sections, and water column profile sampling (from 0 up to 32 m, each 0.5 to 3 m) was done ~~in~~ at 9 sites in the reservoir branches and main basin (Fig. ~~figure~~ 1). Sampling was repeated (with a few exceptions) during four campaigns: 1) November 14th to December 5th 2016 (Nov-Dec 2016), 2) April 19th to May 3rd 2017 (Apr-May 2017), 3) February 28th to March 13th 2018 (Feb-Mar 2018), and 4) August 12th to 29th 2018 (Aug 2018).

2.2 Physical and chemical analyses

Water temperature, dissolved oxygen, and pH were measured using a multi-parameter probe (YSI model 600XLM-M) equipped with a depth gauge and attached to a 12 Volt submersible pump (Proactive Environmental Products model Tornado) for water samples collection. Concentrations of dissolved organic carbon (DOC), total phosphorus (TP), total nitrogen (TN), and chlorophyll a (Chla) were measured during all campaigns in all surface sampling sites (Fig. ~~ure~~ 1). Methods for these analyses are described in detail in (Soued and Prairie, (2020)). Briefly, TP and Chla (extracted with hot ethanol) were analyzed via spectrophotometry, and TN and DOC (filtered at 0.45 µm) were measured on an Alpkem Flow Solution IV autoanalyser and on a Total Organic Carbon analyser 1010-OI respectively.

For each site, we defined the depths of the thermocline and the top and bottom of the metalimnion based on measured temperature profiles using the R package rLakeAnalyzer (Winslow et al., 2018). The epilimnion was defined from the surface to the top of the metalimnion, and was assumed to be a mixed layer.

2.3 Gas concentration, isotopic signature, and water-air fluxes

CO₂ and CH₄ gas concentrations and isotopic signatures ($\delta^{13}\text{C}$) were measured in duplicates at the surface in 36 sites and along vertical profiles in 9 sites (P1 to P9, Fig. ~~ure~~ 1) using the headspace technique described in details in (Soued and Prairie, (2020)). In brief, sampling was done by equilibrating the water sample for two minutes with an air headspace inside a 60 mL syringe. The gas phase was then injected in a 12 mL pre-vacuumed air-tight vial, and analyzed on a gas chromatograph (Shimadzu GC-8A with a flame ionization detector) for gas concentrations, and on a Cavity Ring Down Spectrometer (CRDS) equipped with a Small Sample Isotopic Module (SSIM, Picarro G2201 -i) for $\delta^{13}\text{CO}_2$ and $\delta^{13}\text{CH}_4$.

Surface gas flux data used in this study are described in more details Soued and Prairie (2020), a previous study on the C footprint of Batang Ai reservoir. Surface diffusive fluxes of CO₂ and CH₄ were measured at all surface sampling sites during each campaigns. Flux rates were derived from linear changes in CO₂ and CH₄ concentrations in a static floating chamber (design described in (Soued and Prairie, (2020) and IHA (2010)) connected in a closed loop to a gas analyzer (model UGGA, from Los Gatos Research). Measured gas concentrations, isotopic signature, and fluxes were spatially interpolated to the whole reservoir area by inverse distance weighting (given the absence of a suitable variogram for kriging) using package gstat version

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1.1-6 in the R version 3.4.1 software (Pebesma, 2004). Mean values were calculated for each campaign based on the interpolated maps (Soued and Prairie, 2020).

2.4 Horizontal GHG inputs

130 In order to estimate the external horizontal inputs of CO₂ and CH₄, we considered that the total volume of water inflow and outflow (discharge measured at the dam) were equal, and equivalent to the mean of measured daily discharge (Q, in m³ d⁻¹) during each campaign (considering minimal changes in inflow / outflow rates during a campaign). The approach of using discharge as a measure of total water inflow has the advantage of integrating all external flow (rivers, lateral soils, and groundwater) as water inputs to the reservoir. However, the fraction of inflow feeding the reservoir surface versus bottom layer, and its average gas concentration can only be approximated based on measurements from the two main river inlets (Fig. 1) due to the lack of data on other lateral inflows. Given that part of the ~~water from the riverine inflows~~ inflowing water is colder and denser than the reservoir surface layer, only a fraction of ~~the inflowing waters~~ it enters the epilimnion of the reservoir ~~branches~~, and the rest plunges into the hypolimnion. We estimated ~~that~~ the fraction ~~of inflowing water entering the epilimnion~~ (f_{epi}) based on temperature profiles in the East-at- river delta and branch (sites P1 and P2, Fig. 1) the two ends of the right branch, and assumed it is representative of other water inflows to the reservoir. ~~The~~ areal rate of horizontal CO₂ and CH₄ inputs (H, in mmol m⁻² d⁻¹) over each section of the reservoir were then calculated following Eq. (1):

$$H = \frac{C_{in} Q f_{epi}}{A} \quad (1)$$

with A (in m²) the surface area of the reservoir section considered, and C_{in} (in mmol m⁻³) the concentration of gas in the inflowing water. To estimate gas inputs ~~from~~ the inflows to the branches, C_{in} was considered as the average of gas concentrations measured at the two upstream extremities of the branches (Fig. ~~the~~ 1). To estimate gas inputs from the branches to the main basin, C_{in} was considered as the gas concentrations measured at the confluence between the two branches (right upstream of the main basin).

2.5 Vertical GHG fluxes

150 We estimated CO₂ and CH₄ fluxes from the metalimnion to the epilimnion (V) based on the vertical gas diffusivity (K_z) and the gradient in gas concentration across the epilimnion-metalimnion interface using Eq. (2) (Wüest and Lorke, 2009):

$$V = K_z (C_{meta} - C_{epi}) \quad (2)$$

where C_{meta} and C_{epi} are the gas concentrations at the top of the metalimnion and at the bottom of the epilimnion respectively, measured in profile sites (P1 to P9, Fig. ~~the~~ 1). K_z was derived from the following Eq. (3) (Osborn, 1980):

$$K_z = \Gamma \frac{\epsilon}{N^2} \quad (3)$$

155 where Γ is the mixing ratio set to 0.2 (Oakey, 1982), ϵ is the dissipation rate of turbulent kinetic energy, and N^2 is the buoyancy frequency. N^2 was calculated from measured temperature profiles (YSI probe) using function buoyancy.freq from the rLakeAnalyzer package (Winslow et al., 2018) in the R software (R Core Team, 2017). ϵ was derived from measured vertical

shear microstructure profiles performed in the Aug 2018 campaign in all profile sites shown in Fig. ure 1 (except P1 due to floating logs). Shear profiles were measured with a high frequency (512 Hz) MicroCTD profiler (Rockland Scientific) equipped with two velocity shear probes, two thermistors, tilt and vibration sensors, and a pressure sensor. At each site, the profiler was cast 10 times, 5 with an uprising configuration (from bottom to top of the water column) and 5 with a downward configuration (top to bottom), with a 4 min waiting time between profiles to allow water column disturbance to subside. Data quality check and ϵ calculation for each profile cast were performed with ODAS v4.3.03 Matlab library (developed by Rockland Scientific) based on Nasmith shear spectrum (Oakey, 1982), with ϵ values averaged among the two shear probes and binned over 1-2 m segments along the profile. For each site, continuous ϵ profiles were interpolated by fitting a smooth spline through all ϵ values from replicate casts as a function of depth.

At the epilimnion-metalimnion interface (top of the metalimnion \pm 2 m), calculated ϵ averaged 7.7×10^{-9} (range from 3.4×10^{-9} to 1.6×10^{-8}) $\text{m}^2 \text{s}^{-3}$ across all sites sampled with the microCTD, with no significant difference between the main basin and branches sites. In order to estimate vertical gas diffusion, we applied the latter ϵ average to Eq. (2) and (3) for all measured gas profiles (except P1). The resulting V values for each gas were averaged across sites in the main basin and branches separately to derive estimates of V for each of these two reservoir sections.

2.6 Sediment GHG inputs

We calculated CO_2 and CH_4 inputs from the sediments to epilimnetic waters using gas profiles in sediment cores collected in Apr-May 2017 and Feb-Mar 2018 at 7 sites (P1 to P3 in the reservoir branches and P4, P5, P7, and P9 in the main basin, Fig. ure 1). Sediment cores were collected using a Glew gravity corer attached to a 6-cm-wide plastic liner. The liner was pre-drilled with 1 cm holes covered with electric tape at each centimeter up to 40 cm. Upon recovery of the sediment core, 3 mL tip-less syringes were inserted into each hole to extract sediments from each centimeter. The sediment content of each syringe was emptied into a 25 mL glass vial prefilled with 6 mL nano-pure water and immediately air-tight sealed by a butyl rubber stopper crimped with an aluminum cap. Glass vials were pressurized with 40 mL of ambient air using a plastic syringe equipped with a needle to pierce the rubber cap. Glass vials were shaken for 2 min for equilibration before extracting the gas with a syringe and injecting it into a pre-evacuated air-tight vial for analysis of CO_2 and CH_4 concentrations and isotopic signatures as described above. Additionally, samples of the water overlaying the sediments (~1 cm above) were collected for similar analyses of CO_2 and CH_4 .

Sediment CO_2 and CH_4 flux rates to the overlaying water column were derived from the vertical gradient of gas concentration measured in the sediment cores and overlaying water. The slope of CO_2 or CH_4 concentration as a function of depth (g , in $\mu\text{mol L}^{-1} \text{m}^{-1}$) was calculated for measured values in the first 5 cm of sediments and overlaying water. Most cores exhibited clear linear slopes (p -value < 0.05 and $R^2_{\text{adj}} > 0.5$). In the few cases where a linear slope was not evident, g was replaced by the gradient between the mean gas concentration in the first 3 cm of sediments and the overlaying water. The sediment gas flux rate (S_f in $\text{mmol m}^{-2} \text{d}^{-1}$) were calculated with Eq. (4):

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$$S_f = \frac{g \times d}{p} \quad (4)$$

With d the diffusion coefficient set to $1.5 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$ (Donis et al., 2017), and p the sediment porosity assumed to be 2 % based on previous results in Batang Ai (Tan, 2015).

At an ecosystem scale, sediment CO_2 and CH_4 inputs to the water column (S) were estimated based on average and standard deviation values of sites located in each section of the reservoir (branches and main basin). For each section, mean sediment
 195 CO_2 and CH_4 flux rates were multiplied by the areal ratio of epilimnetic sediments (A_{epi}) versus total water area (A_0). The latter ratio was calculated based on the hypsometric model (Ferland et al., 2014; Imboden, 1973) as shown in Eq. (5) to (7):

$$q = \left(\frac{z_{max}}{z_{mean}} \right) - 1 \quad (5)$$

$$A_{epi} = A_0 \left(1 - \left(1 - \left(\frac{z_{epi}}{z_{max}} \right)^q \right) \right) \quad (6)$$

$$S = \frac{A_{epi}}{A_0} S_f \quad (7)$$

200 with q a parameter describing the general shape of the reservoir section, z_{max} and z_{mean} the maximum and mean depths respectively, and z_{epi} the mean depth of the epilimnion (8.0 and 10.5 m in the branches and main basin respectively).

Littoral sediments are known to be a source of CH_4 not only through diffusion but also via ebullition. While this emission pathway was found to be important in other reservoirs (Deemer et al., 2016), it is surprisingly low in Batang Ai, equaling less than 2 % of CH_4 surface diffusive emissions, and only 0.1 % of the reservoir total GHG footprint (Soued and Prairie, 2020).

205 Therefore, sediment ebullition was considered negligible in the epilimnetic CH_4 budget of Batang Ai.

2.7 Metabolic rates

Net metabolic rates of CO_2 and CH_4 production in the epilimnetic water column were estimated with *in situ* incubations. Incubations were performed in 5 sites (P2 and P3 in the branches and P4, P5 and P7 in the main basin, Fig. ~~ure~~ 1). Water from 3 m deep was pumped into 5 L transparent glass jars with an air tight clamp lid. Before closing, jars were filled from the bottom
 210 and allowed to overflow, then sampled for initial CO_2 and CH_4 concentrations. Closed jars were fixed at 3 m to an anchored line at the sampling site, and incubated in *in situ* temperature and light conditions for 22.0 to 24.2 hours. Upon retrieval, samples of final CO_2 and CH_4 concentrations were collected from the jars. Volumetric daily rates of net CO_2 and CH_4 production were calculated based on the difference between final and initial gas concentrations rescaled to a 24 h period.

In addition to incubations, open water high frequency O_2 measurements were carried out to derive CO_2 metabolism on larger
 215 spatial and temporal scales. Rates of GPP, ER, and net ecosystem production (NEP) were estimated in the reservoir surface layer by monitoring and inverse modeling diel O_2 changes in the epilimnion. O_2 was measured at a one minute interval using high frequency O_2 and temperature sensors (model miniDOT from Precision Measurement Engineering), along with light sensors (model HOBO Pendant from Onset). Sensors were deployed in profile sites P1 to P3 in the branches and P4, P5, P7, and P9 in the main basin (Fig. ~~ure~~ 1). Note that not all sites were sampled in all sampling campaigns. Sensors were attached to

220 an anchored line at a depth between 0.7 and 3 m and deployment time varied between 4 days and two weeks. Upon retrieval of the sensors, a first data quality check and selection was made based on the sensor internal quality index and visual screening. Rates of ecosystem metabolism were then estimated based on an open system diel O₂ model (Odum, 1956), where change in O₂ concentration is a function of GPP, ER, and air-water gas exchange (K_{O2}) following Eq. (8) (Hall and Hotchkiss, 2017):

$$\frac{dO_2}{dt} = \frac{GPP}{z_{epi}} + \frac{ER}{z_{epi}} + K_{O_2} (O_{2sat} - O_2) \quad (8)$$

225 with O_{2sat} the theoretical O₂ concentration at saturation considering the *in situ* temperature and atmospheric pressure, and O₂ is the actual measured O₂ concentration in the water. A detailed description of the model equations can be found in (Hall and Hotchkiss, 2017). Daily estimates of GPP, ER, and K₆₀₀ (based on K_{O2}) were derived by maximum likelihood fitting of the data to the model in Eq. (8) using the R package StreamMetabolizer (Appling et al., 2018). Note that even though the package used was originally developed for streams, it is easily ~~applicable to lakes / reservoirs systems by replacing the depth of the~~

230 ~~stream by the depth of the mixed layer. transferable to lakes given that the model used (Eq. (8)) is generalized for all water bodies, with the parameter z_{epi} describing the depth of a mixed water column of either a lentic or lotic system, and with the K₆₀₀ estimate relying only on data fitting to the model and not on system type.~~ In some cases, where the best predicted K₆₀₀

was negative, the fitting process was rerun with a user defined positive K₆₀₀, either equal to a value estimated for the previous or subsequent day at the same site (range of 0.03 – 0.96 d⁻¹) or fixed to 0.1 d⁻¹ (if no other available estimate). When considering

235 the epilimnion depth, predicted values of K₆₀₀ translate into a 1st to 3rd quantiles range of 1.17 to 5.55 m d⁻¹, which is similar to the range of K₆₀₀ values back-calculated from surface gas flux measurements with the floating chamber technique. A final selection of daily metabolic estimates was done based on the model goodness of fit assessed by calculating Pearson correlation coefficient between modeled and measured O₂ values and discarding days with a correlation lower than 0.9. Based on GPP and ER estimates, we calculated daily NEP as the balance between these two processes, and converted it to net CO₂ production

240 rate by assuming an O₂:CO₂ metabolic quotient of 1.

Areal metabolic rates were derived by integrating volumetric rates over the depth of the epilimnion. Average estimates of areal metabolic rates per campaign were obtained for the branches and main basin by first averaging data within each site and then across sites for each reservoir section. Note that one value derived from incubations was excluded from the calculation of the average net CH₄ production rate in the branches due to its high value of initial CH₄ concentration (an order of magnitude higher than in all other incubations and all epilimnetic data from this site). The high CH₄ concentration, unrepresentative of real conditions, was probably caused by CH₄ contamination during sampling, and triggered a high oxidation rate that would overestimate the real ecosystem average rate if included.

2.8 Epilimnetic GHG budgets

250 Areal rates of horizontal, vertical, sediment, and metabolic inputs were combined into a sum of sources / sinks and compared to the rate of surface gas flux for each gas in each reservoir section. A mean and standard error were calculated for every component of the budgets based on measurements averaged across sites and / or sampling campaigns in order to obtain

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ecosystem-scale estimates of the component means and uncertainties. In the case of CO₂ metabolism, the ecosystem-scale average was calculated as the mean of the two average values derived from the incubation and diel O₂ monitoring methods. For every component, density curves were simulated derived considering a normal distribution based on centered around based the mean and its with a standard deviation equal to the standard error in order to visualize the relative magnitude and uncertainty of each ecosystem-scale areal rate (Fig. 3).

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3 Results

3.1 Physical and chemical properties

Surface water temperature exhibited a marked increase from the inflows to the branches, averaging 27.1 and 30.7 °C respectively (Table 1). There was no difference in surface water temperature between the branches and the main basin. The depth of the epilimnion tended to increase and become more stable along the water flow, going from 1.3 (± 1.6) m in Batang Ai river delta, to 8.0 (± 2.3) m in its branch, and 10.6 (± 1.7) m in the main basin (Table 1). Light penetration exhibited the same spatial pattern, with an increasing Secchi depth along the water flow averaging 1.3, 5.1, and 5.5 m in the inflows, branches, and main basin respectively (Table 1). All sections of the study system exhibited oligotrophic water properties (Table 1).

3.2 Surface GHG concentrations, fluxes, and isotopic signatures

Surface CO₂ and CH₄ patterns are summarized in Fig. 2, presenting campaign averages of spatially interpolated gas concentration, flux, and isotopic signature along the different reservoir sections. Despite the temporal variability, the gas patterns along the water flow are robust, remaining similar throughout time (Fig. 2).

Average CO₂ air-water flux and surface concentration were systematically higher in the inflows (mean [range]: 135.3 [18.9 – 368.8] mmol m⁻² d⁻¹ and 58.0 [24.5 – 113.0] μmol L⁻¹, respectively) compared to the branches (4.7 [-3.4 – 15.2] mmol m⁻² d⁻¹ and 15.4 [12.2 – 19.3] μmol L⁻¹) and main basin (7.5 [0.3 – 15.1] mmol m⁻² d⁻¹ and 16.0 [14.2 – 17.7] μmol L⁻¹) (Fig. 2a, b). Surface CO₂ concentration in the reservoir (branches and main basin) was most strongly correlated inversely with water temperature (R²_{adj} = 0.22, p-value < 0.001, Fig. S1a and Table S1). Except for the Apr-Mar 2017 campaign, there was a modest increase (2.2 to 3.3 ‰) of surface δ¹³C_{CO₂} towards more enriched values (2.2 to 3.3 ‰) from the inflows to the branches (Fig. 2c).

Similarly, surface CH₄ flux and concentration continually decreased along the water channel, being an order of magnitude higher in the inflows compared to the branches, and about twice as high in the branches compared to the main basin (Fig. 2d, e). Of all measured water properties, TN was the most strongly linked to reservoir surface CH₄ concentration (R²_{adj} = 0.14, p-value < 0.001, Fig. S1b and Table S1). In the main basin surface CH₄ concentration significantly decreased with distance to shore in Nov-Dec 2016 (R²_{adj} = 0.54, p-value < 0.001), but this correlation was weaker (R²_{adj} ≤ 0.13, p-value ≥ 0.03) during other sampling campaigns (Fig. 6a). Surface δ¹³C_{CH₄} values varied widely, between -83.3 and -47.6 ‰, but did not show a

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consistent spatial pattern (Figure Fig. 2f) apart from a positive correlation with distance to shore in the main basin in Nov-Dec 2016 ($R^2_{\text{adj}} = 0.29$, p-value = 0.01, Fig. 6b).

285 The degree of coupling between CO₂ and CH₄ followed a clear spatial pattern. While CO₂ and CH₄ surface concentrations were strongly linked in the inflows ($R^2_{\text{adj}} = 0.54$, p-value = 0.006), they became only weakly correlated in the branches ($R^2_{\text{adj}} = 0.17$, p=0.005) and not correlated at all in the main basin ($R^2_{\text{adj}} = 0.01$, p-value = 0.11) (Figure S2).

3.3 Horizontal GHG flow

290 Horizontal inputs from the inflows to the surface layer of the branches were estimated to vary between 0.34 – 0.71 mol s⁻¹ for CO₂ and 0.02 – 0.25 mol s⁻¹ for CH₄. When expressed as rates over the branches surface area (to facilitate comparison with other components), this results in 2.7 – 5.7 and 0.16 – 1.972.0 mmol m⁻² d⁻¹ for CO₂ and CH₄ respectively (Table S2 and S3). These values are in the same order of magnitude as surface fluxes calculated in the branches (Figure 3a, c, and Table S2 and S3). However, the effect of horizontal inputs faded spatially, with much lower inputs from the branches to the main reservoir basin, averaging 0.31 and 0.004 mmol m⁻² d⁻¹ for CO₂ and CH₄, respectively (Figure 3b, d and Table S2 and S3). For CH₄, this fits spatial and temporal surface flux measurements, being systematically higher in the branches, and maximal during the two sampling campaigns with the highest recorded horizontal inputs from the inflows (Table S3). In contrast, CO₂ surface flux was typically lower (sometimes negative) in the branches compared to the main basin, despite substantial riverine inputs to the branches (Table S2).

3.4 Vertical GHG inputs

300 Vertical fluxes depend on the gas diffusivity and concentration gradient. Gas diffusivity is a function of the strength of stratification (N^2) and energy dissipation rate (ϵ). Measured values of N^2 and ϵ varied widely, from 5.9×10^{-5} to $2.3 \times 10^{-3} \text{ s}^{-2}$ and from 3.4×10^{-9} to $1.6 \times 10^{-8} \text{ m}^2 \text{ s}^{-3}$ respectively, but with no clear differences between the reservoir branches and main basin (Figure S3a, b). Similarly, CO₂ and CH₄ concentration gradients varied substantially in both space and time (from -18.4 to 94.3 $\mu\text{mol L}^{-1} \text{ m}^{-1}$ for CO₂ and -0.19 to 0.4 $\mu\text{mol L}^{-1} \text{ m}^{-1}$ for CH₄). CO₂ concentration generally increased from the epilimnion to the metalimnion as a result of the respiratory CO₂ buildup in the deep layer. On rare occasions, an inverse gradient was observed, possibly due to autotrophic activity in the metalimnion. For CH₄, metalimnion to epilimnion concentration gradients were generally modest averaging 0.04 $\mu\text{mol L}^{-1} \text{ m}^{-1}$, and even negative in one third of the profiles leading to the diffusion of epilimnetic CH₄ toward deeper layers instead of the reverse. The low to negative CH₄ vertical flux results from a highly active methanotrophic layer reducing CH₄ concentration in the metalimnion, as evidenced by the strong enrichment effect observed in $\delta^{13}\text{C}_{\text{CH}_4}$ profiles (Figure S4). The combination of vertical diffusivity and gas concentration gradients resulted in vertical fluxes averaging 3.4 (-1.8 to 20.5) mmol m⁻² d⁻¹ for CO₂, and 0.01 (-0.01 to 0.09) mmol m⁻² d⁻¹ for CH₄, with no significant differences between the reservoir branches and main basin (Figure S3).

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3.5 GHG inputs from littoral sediments

Areal sediment gas fluxes ranged from 1.2 to 4.0 and -0.29 to 1.10 mmol m⁻² d⁻¹ for CO₂ and CH₄, respectively (Fig. ure S5), in the range of previously reported values in lakes and reservoirs (Adams, 2005; Algesten et al., 2005; Gruca-Rokosz and Tomaszek, 2015; Huttunen et al., 2006). Sediment fluxes were not different in the branches versus the main basin for both CO₂ (mean of 2.2 vs 2.4 mmol m⁻² d⁻¹) and CH₄ (mean of 0.17 vs 0.48 mmol m⁻² d⁻¹) (Fig. ure S5). Applying measured averages to the area of epilimnetic sediments in each section yields estimates of sediment inputs to the epilimnion of 0.6 (± 0.03) and 0.5 (± 0.11) mmol m⁻² d⁻¹ for CO₂, and 0.04 (± 0.02) and 0.10 (± 0.06) mmol m⁻² d⁻¹ for CH₄ in the branches and main basin respectively (Fig. ure 3 and Table S2 and S3). These inputs from littoral sediments likely represent an upper limit since they are based on deep pelagic sediment cores (littoral area were too compact for coring), where a higher organic matter accumulation and degradation is expected (Blais and Kalff, 1995; Soued and Prairie, 2020). Even as upper estimates, the calculated rates of sediment GHG inputs remain a relatively modest fraction of the average emissions to the atmosphere for the branches and main basin both for CO₂ (13 % and 7 %, respectively) and CH₄ (4 % and 23 %, respectively) (Tables S2 and S3).

3.6 Metabolism

3.6.1 CO₂ metabolism

Estimated GPP and ER rates based on diel O₂ monitoring ranged from 3.6 to 34.5 μmol L⁻¹ d⁻¹ and from 5.8 to 29.5 μmol L⁻¹ d⁻¹ respectively (Fig. ure 4a), which is well within the range of reported rates for oligotrophic systems (Bogard and del Giorgio, 2016; Hanson et al., 2003; Solomon et al., 2013). As expected, GPP and ER rates were correlated (R²_{adj} = 0.23, p-value < 0.001, Fig. ure 4a), with photosynthesis stimulating the respiration of produced organic matter. In most cases, GPP exceeded ER, especially in the branches and near aquacultures (Fig. ure 4a), where higher nutrients (TP and TN) and Chla concentrations were measured (Table 1). Daily metabolic rates showed no correlation with mean daily rain or light (Kendall rank correlation p-value > 0.1).

In the reservoir branches, results from the diel O₂ monitoring method suggested systematic net CO₂ uptake ranging from -19.2 to -1.4 μmol L⁻¹ d⁻¹, whereas results from two incubations were slightly above that range (-0.5 to 3.3 μmol L⁻¹ d⁻¹) (Fig. ure 4b). In the main basin, the two methods incubation results ranged from -8.8 to 7.2 μmol L⁻¹ d⁻¹ matched fairly well, with while the diel O₂ technique capturing a wider variability in net CO₂ metabolic rates ranging from -19.2 to 6.1 μmol L⁻¹ d⁻¹, with an estimated CO₂ uptake in 39 out of 54 cases (Fig. ure 4b). Areal net CO₂ metabolic rates, as the average of the two methods, yielded an ecosystem-scale estimate of -23.2 and -11.8 mmol m⁻² d⁻¹ in the reservoir branches and main basin, respectively (Table S2).

To complement the metabolic rate data, surface O₂ and CO₂ departure from saturation were examined in both reservoir sections. O₂ oversaturation was observed in 44 % of cases in the main basin and 81 % in the branches (Fig. 5), which corresponds with

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the spatial patterns of net metabolic rates (Fig. 4b). CO₂ oversaturation was also widespread (74 % of cases), making many sampled sites oversaturated in both O₂ and CO₂ (55 % in the branches and 32 % in the main basin, Fig. 5).

3.6.2 CH₄ metabolism

Net metabolic CH₄ rates (from incubations) ranged from -0.026 to 0.078 μmol L⁻¹ d⁻¹, indicating that the CH₄ balance in the epilimnion of Batang Ai varied from net oxidation to net production (Table S3). CH₄ metabolic rates measured in Batang Ai are within the range of values observed in other systems for oxidation (Guérin and Abril, 2007; Thottathil et al., 2019) and production (Bogard et al., 2014; Donis et al., 2017). No temporal or spatial (branches versus main basin) differences in net metabolic CH₄ rate were detected due to a high variability and limited data points.

3.7 Ecosystem scale GHG budgets

Estimated sources / sinks of CO₂ and CH₄ were collated into a budget to evaluate their relative impact on epilimnetic gas concentration and to assess whether their sum matches the measured surface gas fluxes in each section of the reservoir. Fig. 3 depicts such reconstruction of the epilimnetic CO₂ and CH₄ budgets in Batang Ai, as well as the uncertainty limits of each component. While each process varied in time, their relative importance in driving surface fluxes was generally similar from one sampling campaign to another (Table S2 and S3).

3.7.1 CO₂ budget

For CO₂, epilimnetic sediment inputs had the smallest contribution, being typically an order of magnitude lower than measured surface fluxes in both sections of the reservoir (Fig. 3a, b and Table S2). Vertical CO₂ inputs from lower depths on the other hand contributed substantially to surface fluxes in both the branches and especially in the main basin (mean of 0.7 and 4.5 mmol m⁻² d⁻¹ respectively) (Fig. 3a, b and Table S2), indicating that hypolimnetic processes impact surface emissions despite the permanent stratification. Horizontal inputs of CO₂ were in the same range as vertical inputs (mean of 4.3 mmol m⁻² d⁻¹) in the branches, however, they decreased by an order of magnitude when reaching the main basin (mean of 0.3 mmol m⁻² d⁻¹). Thus, direct CO₂ inputs from the inflows notably increase surface flux rates in the reservoir branches but only minimally in the main basin. Net CO₂ metabolism was surprisingly variable (switching from negative to positive NEP on a daily time scale), thus making it difficult to derive a sufficiently precise ecosystem-scale estimate to close the epilimnetic budget (Fig. 3a, b), despite high sampling resolution (n = 66 daily metabolic rates). Including the metabolism substantially shifts the mean of the CO₂ epilimnetic budget (sum of sources and sinks) to a negative value and drastically increases its uncertainty (Fig. 3a, b and Table S2), reflecting a potentially important but poorly resolved role of metabolism in the budget because of its variability. However, given that metabolism acts more likely as a CO₂ sink on average, Nevertheless, estimated net water column CO₂ metabolism had a considerable impact on the epilimnetic budget, but acts more likely as a CO₂ sink rather than a source in Batang Ai (Figure 3 and Table S2). Our best assessment suggests that in the

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375 main basin, vertical transport from deeper layers is the main source sustaining surface CO₂ out-flux in the main basin of Batang

Ai.

3.7.2 CH₄ budget

380 In contrast with CO₂, vertical transport was the smallest source of CH₄ to the epilimnion, contributing to ~~less than~~ only 2 % ~~to~~
of surface fluxes in both reservoir sections (Fig. ~~ure~~ 3c, d and Table S3). In the branches, sediment inputs and net CH₄ metabolic
385 rates were both relatively low (mean of 0.04 ± 0.02 and 0.04 ± 0.05 mmol m⁻² d⁻¹) and had little impact on the budget,
corresponding each to 4 % of surface fluxes in that section (Fig. ~~ure~~ 3c and Table S3). On the other hand, horizontal inputs
were the dominant and most variable source sustaining CH₄ emissions in the branches, where the epilimnetic mass balance
closed almost perfectly (Fig. ~~ure~~ 3c and Table S3). Despite being the main CH₄ source in the branches, horizontal transport
was a negligible component in the main basin (<1 % of the flux, Fig. ~~ure~~ 3d and Table S3). Instead, sediment inputs played a
larger role in that section, with a mean of 0.10 (± 0.06) mmol m⁻² d⁻¹, fueling ~~232~~ 23 % of surface emissions in the main basin
385 (Fig. ~~ure~~ 3d and Table S3). As with CO₂, the most variable CH₄ component of the mass balance in the main basin was the net
metabolism within the epilimnion (mean of -0.16 ± 0.19 mmol m⁻² d⁻¹). Considering all sources, the CH₄ budget indicates a
deficit of 0.34 mmol m⁻² d⁻¹ to explain measured surface emissions in the main basin (Fig. ~~ure~~ 3d and Table S3).

4 Discussion

390 Our results have highlighted both the importance and the challenges associated with quantifying simultaneously all the
components of the epilimnetic CO₂ and CH₄ budgets, particularly in a hydrologically complex reservoir system. While mass
fluxes (hydrological, sedimentary, and air-water fluxes) are relatively easy to constrain, internal C processing, namely the net
metabolic balances between production and consumption of CO₂ and CH₄ are highly dynamic in both time and space, leading
to significant uncertainties when extrapolated to the ecosystem scale. In many studies, some components are only inferred by
395 difference. While convenient from a mass-balance perspective, we argue that assessing all components together is necessary
to clearly identify knowledge gaps as well as sources of uncertainty.

4.1 Spatial dynamics of CO₂ and CH₄

The decrease in gas concentration and air-water fluxes along the hydrological continuum observed across sampling campaigns
and for both CH₄ and CO₂ reflects a robust spatial structure of the gases. Concurrently, estimates of the horizontal GHG inputs
shows a clear and consistent spatial pattern, being high in the branches but negligible in the main basin. A temporal effect of
400 riverine inputs was also observed as the two sampling campaigns with the highest horizontal CH₄ inputs coincided with the
highest CH₄ emissions in the branches (Table S3). All these results concord with ~~the a~~ progressively reduced influence of
direct GHG catchment inputs and greater preponderance of internal processes along the hydrological ~~flow-continuum as~~

observed in river networks (Hotchkiss et al., 2015) and in lakes and reservoirs (Chmiel et al., 2020; Loken et al., 2019; Paranaíba et al., 2018; Pasche et al., 2019).

405 For CO₂, the sharpest change in surface metrics (concentration, flux, and isotopic signature) was observed between the inflows and the reservoir branches (Fig. ure-2a, b, c). Despite large riverine inputs (Table S2), the branches exhibited low CO₂ concentration and fluxes, as well as an increase in δ¹³CO₂ matching with high GPP values (Fig. ure 2a, b, c and 4a). This may reflect increased light availability for phytoplankton when transitioning from the turbid inflows to the reservoir branches (higher Secchi depth, Table 1), a pattern previously reported in other reservoirs (Kimmel and Groeger, 1984; Pacheco et al., 410 2015; Thornton et al., 1990). While the branch areas are often associated with high CO₂ outflux due to riverine inputs (Beaulieu et al., 2016; Paranaíba et al., 2018; Pasche et al., 2019; Roland et al., 2010; Rudorff et al., 2011), they are occasionally observed to have low air-water flux due to simultaneous nutrient inputs (Loken et al., 2019; Paranaíba et al., 2018; Wilkinson et al., 2016). In Batang Ai, inflows have a high nutrients (TP and TN) to DOC ratio compared to the reservoir branches (Table 1), providing higher inputs of nutrients relative to organic matter, and thus likely stimulating primary production more than 415 respiration. This hypothesis is consistent with a higher GPP: ER ratio and mean Chla concentrations measured in the branches compared to the main basin (Fig. ure 4a and Table 1). The variability of CO₂ concentration within the reservoir (branches and main basin) was negatively correlated to temperature, likely due to its effect on GPP (Bogard et al., 2020). This further highlights the important role of primary production in modulating CO₂ dynamics throughout the reservoir, and particularly in the branches.

420 The correlation between surface CH₄ surface- and TN in the reservoir suggests that primary production may also affect CH₄ dynamics. Nutrient content was shown in previous studies to enhance CH₄ production in the sediments (Beaulieu et al., 2019; Gebert et al., 2006; Isidorova et al., 2019) and in the oxic water column (Bogard et al., 2014), through its link with algal production and decomposition. However, CH₄ concentration and flux variability were strongly driven by a spatial / hydrological structure, gradually decreasing from the inflows to the main basin. This likely reflects the combined effect of 425 terrestrial inputs and a decreasing contact of water with sediments along the water channel. Surface δ¹³CH₄ signatures varied substantially but without a consistent spatial pattern (Fig. ure 2f), indicating that the surface CH₄ pool is shaped by multiple sources / processes (metabolism, riverine, and sediment inputs) varying through space and time.

~~TO~~Overall, the changing relative contribution of sources and processes shaping surface CO₂ and CH₄ concentrations varies with the system hydro-morphology, from the inflows to the main reservoir basin, and lead to a progressive decoupling between the 430 two gases along the continuum (Fig. ure S2). The observed CO₂ and CH₄ coupling in the inflows and branches is associated to a common catchment source, as previously reported in other systems including soil-water (Lupon et al., 2019), streams (Rasilo et al., 2017), and lake and reservoir inflow areas (Loken et al., 2019; Natchimuthu et al., 2017; Paranaíba et al., 2018). Indeed, horizontal inputs are the main source of both CO₂ and CH₄ in the upstream reaches of Batang Ai, accounting on average for 91 and 92 % of their respective surface out-flux in the branch section (Fig. 3a, c and Tables S2 and S3). However, when 435 reaching the main basin, driving sources diverge between the two gases, with vertical inputs from the bottom layer supporting on average 60 % of CO₂ compared to 2 % of CH₄ fluxes, while sediment inputs sustained 7 versus 23 % of CO₂ and CH₄ fluxes

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respectively in that section. This decoupling partly results from the two gases having distinct metabolic pathways: mainly aerobic for CO₂ and anaerobic for CH₄, leading to their sources and sinks being spatially disconnected in the main basin. Consequently, sediments being a mostly anaerobic environment are a more important source of CH₄ relative to CO₂, while the metalimnetic layer being oxic-hypoxic acts as a sink of CH₄ and source of CO₂ via aerobic CH₄ oxidation (Fig. S4). Thus, while CO₂ and CH₄ were both influenced by horizontal inputs in the upstream section, their main drivers diverge in the main basin, with CO₂ mostly shaped by vertical inputs and aerobic metabolism, and CH₄ by sediment inputs and anaerobic metabolism. Overall, the spatial patterns reported here highlight the hydrodynamic zonation common in reservoirs and its diverging effect on CO₂ versus CH₄ cycling.

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445 4.2 CO₂ metabolism

Our observation that GPP often exceeded ER (Fig. ure 4a) was not unexpected given the very low DOC concentration (< 1 mg L⁻¹). Previous work has reported that DOC > 4 mg L⁻¹ is required to sustain persistent net heterotrophy and CO₂ evasion (Hanson et al., 2003; Prairie et al., 2002). Throughout the reservoir, we found high day-to-day variability in both ER and GPP, but with no apparent link to weather data (light and rain, data not shown). The absence of such a link at a daily time scale has been previously reported (Coloso et al., 2011), while other studies associated daily variations in metabolism with changes in water inflows carrying nutrients (Pacheco et al., 2015; Staehr and Sand-Jensen, 2007), or thermocline stability regulating hypolimnetic water incursions to the epilimnion. Such variations in thermocline depth are thought to be more common in warm tropical systems (Lewis, 2010), and were observed across sampling campaigns in Batang Ai, especially in the branches where the depth of the mixed layer varied considerably (SD = 2.3 m, Table 1). Hence, hydrological and physical factors may regulate spatial and daily patterns of GPP and ER rates in Batang Ai through their influence on nutrient dynamics.

The accuracy of rates derived from diel O₂ monitoring partly depends on the respiratory and photosynthetic quotients (RQ and PQ) assumed for the conversion of metabolic rates from O₂ to CO₂. A quotient differing from the assumed 1:1 ratio can lead to an under or over-estimation of net CO₂ production. The fact that net CO₂ metabolic rates were on average higher in incubations, based on direct CO₂ measurements compared to diel O₂ monitoring (Fig. ure 4b and Table S2), hints at a deviation of the metabolic quotients from unity in Batang Ai. Additionally, surface O₂ versus CO₂ concentrations shows that the departure of these gases from saturation varies widely around the expected 1: -1 line (Figure 5). O₂ oversaturation was observed in 44 % of cases in the main basin and 81 % in the branches (Figure 5), which corresponds with the spatial patterns of net metabolic rates (Figure 4). CO₂ oversaturation was also widespread (74 % of cases), making, with half themany surface samples oversaturated in both O₂ and CO₂, especially in the branches (Fig. 5). This indicates an excess O₂ and / or CO₂ that can be due to a PQ and / or a RQ higher than 1, or to external CO₂ inputs to the epilimnion (Vachon et al., 2020), for instance from the inflows or the bottom layer (Table S2). Metabolic quotients have been shown to vary widely, depending on the type and magnitude of photochemical and biological reactions at play (Berggren et al., 2012; Lefèvre and Merlivat, 2012; Vachon et al., 2020; Williams and Robertson, 1991). For instance, CH₄ oxidation and production, evidently occurring in Batang Ai's epilimnion (Table S2 and S3), diverge from the metabolic O₂:CO₂ ratio of one, with CH₄ oxidation consuming two moles of

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470 O₂ for each mole of CO₂ produced, and acetoclastic methanogenesis producing CO₂ without O₂ consumption. Even though net
CH₄ processing rates are a minor portion of the epilimnetic C cycling in Batang Ai (1-2 orders of magnitudes lower than CO₂
metabolic rates, Tables S2 and S3), these reactions (and other unmeasured processes) have the potential to alter the O₂:CO₂
metabolic quotient at an ecosystem scale. The lack of direct measure of metabolic quotients in Batang Ai adds uncertainty to
the net CO₂ metabolism estimates based on O₂ data. The observed decoupling of O₂ and CO₂ metabolism in Batang Ai
475 highlights the need for a deeper understanding of the biochemical reactions occurring in the epilimnion, and their effect on
metabolic quotients.

Overall, our results from Batang Ai reservoir point to water column metabolism as both a ~~major-key~~ process in the CO₂
epilimnetic budget and a challenging one to estimate at an ecosystem scale (Fig. ~~ure~~ 3a, b). Improving this requires a better
mechanistic knowledge of the physical and biochemical processes at play and how they interact to shape NEP.

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4.3 CH₄ metabolism

Incubation results exhibited a wide range of net CH₄ metabolism: from net oxidation to net production. CH₄ oxidation is known
to be highly dependent on CH₄ availability and is optimal in low oxygen and low light conditions (Borrel et al., 2011; Thottathil
et al., 2018, 2019), whereas CH₄ production in the oxic water is still poorly understood but have been frequently linked to
485 phytoplankton growth (Berg et al., 2014; Bogard et al., 2014; Lenhart et al., 2015; Wang et al., 2017). A large variability in
results exists among the studies that have assessed the net balance of CH₄ metabolism in the water column, with some studies
reporting pelagic CH₄ production as a largely dominant process (Donis et al., 2017) while others find no trace of it (Bastviken
et al., 2008). Based on spatial patterns of surface CH₄ concentration and isotopic signature with distance to shore, DelSontro
et al. (2018b) showed that, in 30 % of their studied temperate lakes, CH₄ oxidation was dominant versus 70 % dominated by
490 net pelagic production. In Batang Ai, surface δ¹³CH₄ values were highly variable (-82.5 to -47.7 ‰) but mostly uncorrelated
with distance to shore, except a positive correlation indicative of oxidation in the Nov-Dec 2016 (R²_{adj} = 0.29, p-value = 0.01,
[Fig. 6b](#)) coinciding with a strong inverse pattern for CH₄ concentration (R²_{adj} = 0.54, p-value < 0.001, [Fig. ure 6a](#)). This suggests
a temporal shift in processes driving surface CH₄ patterns. Also, some measured surface δ¹³CH₄ values were lower than the
mean δ¹³CH₄ from the sediments (-66.0 ‰, unpublished data), suggesting another highly depleted source of pelagic CH₄ in the
495 system. This is in line with water incubation results often showing positive net CH₄ production (Table S3). When reported as
mean areal rates, CH₄ metabolism ranged from net consumption to net production of CH₄ (-0.29 to 0.94 mmol.m⁻².d⁻¹), [which](#)
[reflects its potential in having a high impact, either positive or negative, and had a strong influence](#) on the epilimnetic CH₄
budget at the reservoir scale (Fig. [ure](#) 3d and Table S3). Results in Batang Ai show that the net balance of CH₄ metabolic
processes varies widely even within a single system. However, the factors regulating this balance remain largely unknown.
500 Investigating such factors constitute a key step in resolving CH₄ budgets in lakes and reservoirs.

4.4 Epilimnetic GHG budgets

For CO₂, measured surface fluxes in both reservoir sections fall in the range of possible values estimated by the sum of epilimnetic processes and their uncertainties (Figure 3a, b and Table S2). However, the averages of those two terms differ substantially, due to negative values of metabolism shifting the mean of the mass balance towards net CO₂ consumption whereas, on average, surface out-flux was measured from the reservoir. This discrepancy indicates either a missing source of CO₂ in the budget or the underestimation of one of the processes. While lateral groundwater input is a potential source not explicitly considered, it is probably modest given the small ratio of littoral area to epilimnion volume, and is unlikely to account for the large CO₂ deficit in the budget. On the other hand, underestimation of the CO₂ metabolic balance is much more likely, given its large variability and uncertainty around its mean value. Additionally, a systematic underestimation of the CO₂ metabolic rates derived from the diel O₂ method is very possible in Batang Ai given the likely deviation of metabolic quotients around the 1:1 line. As an example, when setting the photosynthetic quotient to 1.2 instead of 1, which remains well within the literature range (Lefèvre and Merlivat, 2012; Williams and Robertson, 1991), the average epilimnetic CO₂ mass balance would increase from -17.7 to 4.3 mmol m⁻² d⁻¹ in the branches and from -6.5 to 6.2 mmol m⁻² d⁻¹ in the main basin, closely matching measured surface fluxes of 4.7 and 7.5 mmol m⁻² d⁻¹ in the respective sections. Thus, constraining the metabolic component, especially the O₂: CO₂ quotients, is key for closing the CO₂ epilimnetic budget.

In the case of CH₄, the epilimnetic mass balance in the branches is surprisingly close to the observed surface flux, largely fueled by horizontal inputs. Hence, CH₄ emissions from the branches reflect catchment CH₄ loads rather than internal processes. However, in the main basin, these inputs become negligible and the estimated budget does not match measured emissions, indicating a deficit of 0.49 mmolCH₄ m⁻² d⁻¹. This amount cannot be explained by a potential underestimation of horizontal or vertical inputs since they are two orders of magnitude lower. Similarly, sediment inputs would need to be six time higher than estimated to fulfill the budget deficit, which is unlikely given their much lower range of uncertainty. Thus, the most plausible source to close the mass balance in the main basin would be water column CH₄ production. Although the estimated CH₄ metabolism indicates an average net consumption rather than a net production (-0.16 mmol m⁻² d⁻¹), this mean value is based on only 3 data points and has a high uncertainty associated to it (SE = 0.19 mmol m⁻² d⁻¹, Table S3). Closing the mass balance would require a net volumetric CH₄ production of about 0.03 μmol L⁻¹ d⁻¹ in the water column of the main basin. This value seems plausible since an equal production rate was measured in one of the incubations, and it is at the low end of the range reported in other systems (Bogard *et al.*, 2014 ; DelSontro *et al.*, 2018b ; Donis *et al.*, 2017). The combination of our results ~~point to suggests that~~ water column metabolism ~~ascould be~~ the dominant source of CH₄ in the main basin of Batang Ai, ~~potentially~~ sustaining up to 75 % of surface emissions in that reservoir section. However, this process seems highly dynamic and requires more intensive research into its controls at spatial and temporal scales, commensurate with CH₄ emissions.

5 Conclusion

The estimated epilimnetic CO₂ and CH₄ budgets in Batang Ai has helped define the role of different processes in shaping the reservoir surface GHG fluxes to the atmosphere. Results showed that horizontal riverine inputs are important sources of GHG in the reservoir branches (especially for CH₄). This creates a coupling between CO₂ and CH₄ close to the river deltas, which gradually fades along the water flow, until the surface concentrations of the two gases become completely uncoupled in the main basin being driven by different sources. For instance, vertical inputs from the bottom layer contributed significantly to surface CO₂ saturation, while being negligible in the case of CH₄ due to metalimnetic oxidation. Inversely, sediment inputs played a notably greater role in sustaining epilimnetic oversaturation of CH₄ compared to CO₂ in the main basin. Nonetheless, the epilimnetic budgets of both gases ~~presented a high sensitivity to were heavily impacted by their respective~~ water column metabolism. This result is likely representative of large systems with a high volume of water versus sediments, which is common for hydroelectric reservoirs. ~~The However,~~ metabolic balances of CO₂ and CH₄ were ~~also~~ extremely variable in space and time, switching from a net production to a net consumption of the gases, and leading to highly uncertain ecosystem-scale estimates, ~~which emphasizes the key but unconstrained role of metabolism in the overall GHG budgets.~~ Factors driving these metabolic changes are not well ~~constrained defined~~ based on current knowledge, highlighting the need for further research on the subject. Overall, this study gives an integrative portrait of the relative contribution of different sources to surface CO₂ and CH₄ fluxes in a permanently stratified reservoir including its transition zones (branches). Conclusions and insights derived from this work likely reflect C dynamics in other similar systems, and highlight knowledge gaps guiding future research to better understand and predict aquatic GHG fluxes and regulation.

550 Author contribution

CS contributed to conceptualization, methodology, validation, formal analysis, investigation, data curation, writing - original draft, writing – review and editing, and project administration. YTP contributed to Methodology, validation, investigation, resources, writing – review and editing, supervision, and funding acquisition.

Competing interests

555 The authors declare that they have no conflict of interest.

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Table 1: Mean (\pm SD) of physical and chemical variables measured at the surface of the three reservoir sections.

| Variables | Units | Inflows | Branches | Main basin |
|----------------|-------------------------|--------------------|--------------------|-------------------|
| z_{epi} | m | 1.3 (\pm 1.6) | 8 (\pm 2.3) | 10.6 (\pm 1.7) |
| Secchi | m | 1.2 (\pm 0.9) | 5.1 (\pm 1.2) | 5.5 (\pm 1.2) |
| Temperature | $^{\circ}$ C | 27.1 (\pm 2.5) | 30.7 (\pm 0.5) | 30.6 (\pm 0.5) |
| pH | | 6.5 (\pm 0.3) | 7.2 (\pm 0.2) | 7.2 (\pm 0.2) |
| O ₂ | % | 94.9 (\pm 7.7) | 102.7 (\pm 4.5) | 99.3 (\pm 4.8) |
| DOC | mg L ⁻¹ | 0.8 (\pm 0.4) | 0.9 (\pm 0.2) | 0.9 (\pm 0.2) |
| TP | μ g L ⁻¹ | 20.7 (\pm 7.6) | 6.2 (\pm 1.7) | 5.8 (\pm 2.6) |
| TN | mg L ⁻¹ | 0.14 (\pm 0.04) | 0.12 (\pm 0.04) | 0.1 (\pm 0.03) |
| Chla | μ g L ⁻¹ | 2.1 (\pm 1.7) | 1.7 (\pm 1) | 1.2 (\pm 0.5) |

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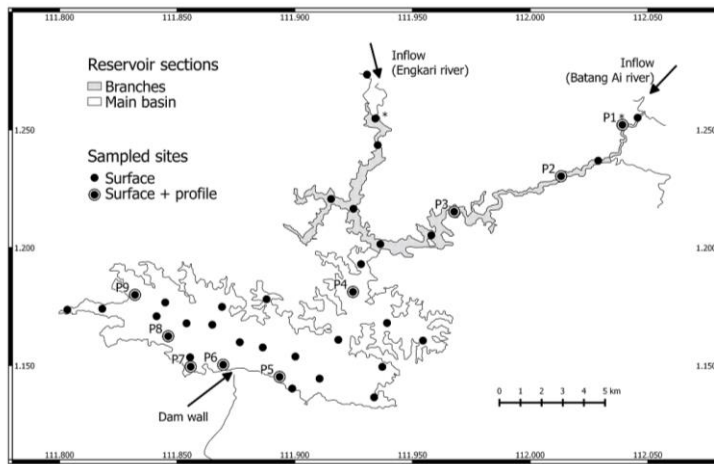
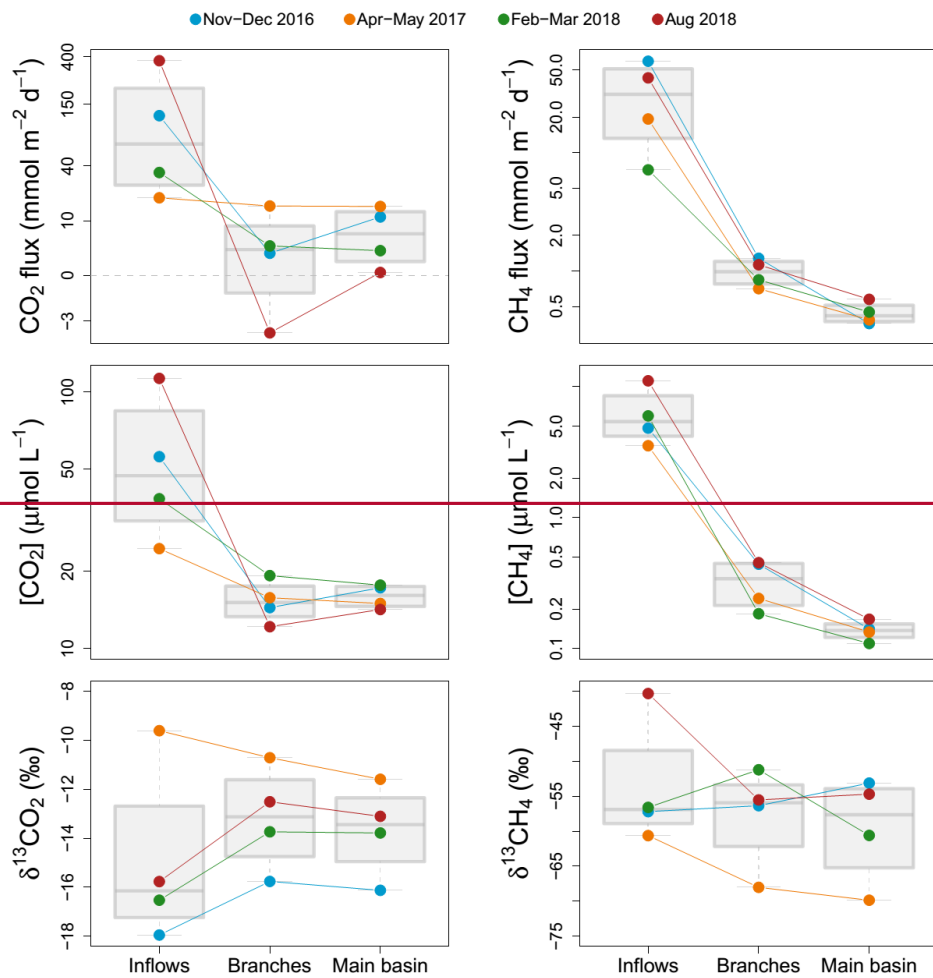


Figure 1: Map of Batang Ai reservoir with delimited sections (branches and main basin) and sampling points. * Represents sampling points at the branches extremities.



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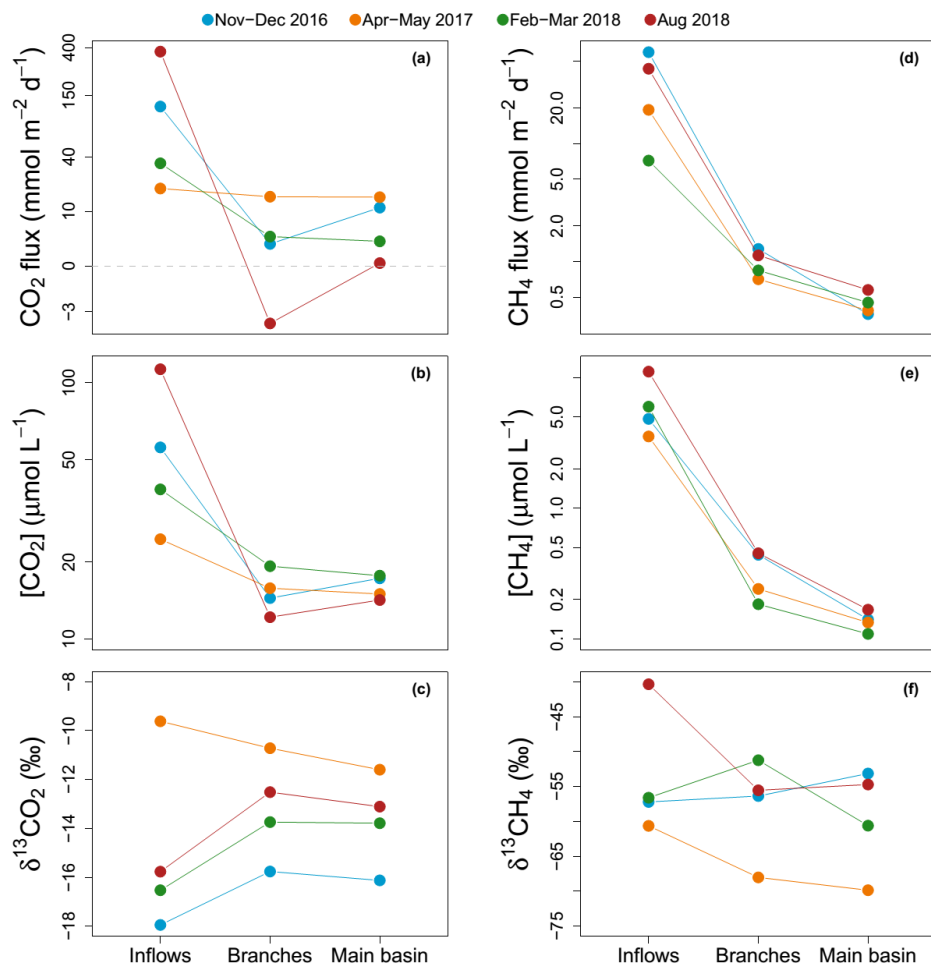
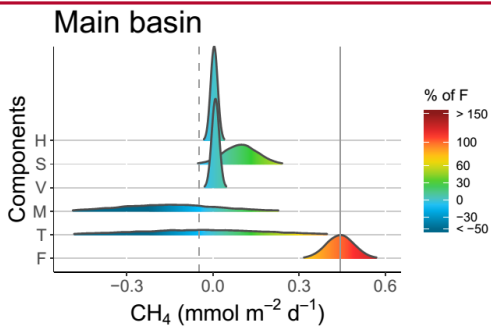
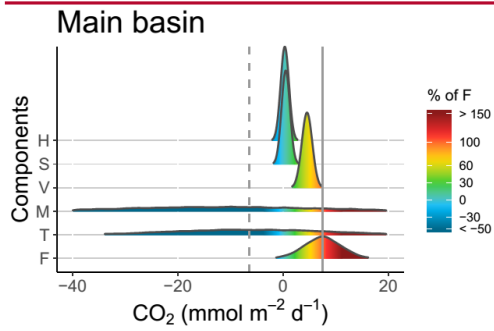
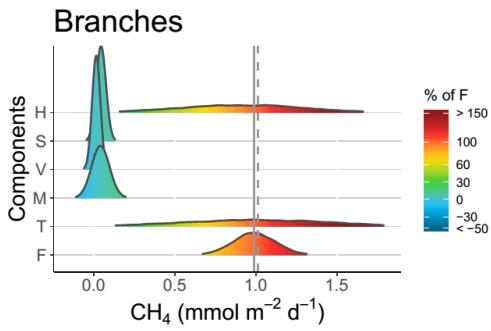
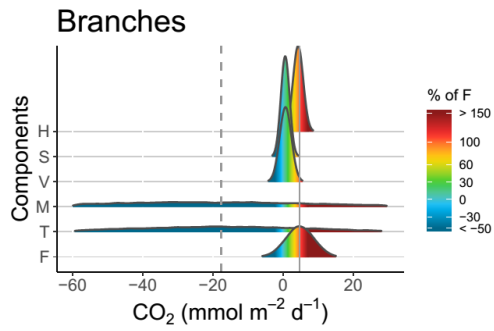


Figure 2: Average of spatially interpolated surface CO₂ (a, b, c) and CH₄ (d, e, f) fluxes (a, d), concentrations (b, e), and isotopic signatures (c, f) along the hydrological continuum from the reservoir inflows to the main basin for each sampling campaign.



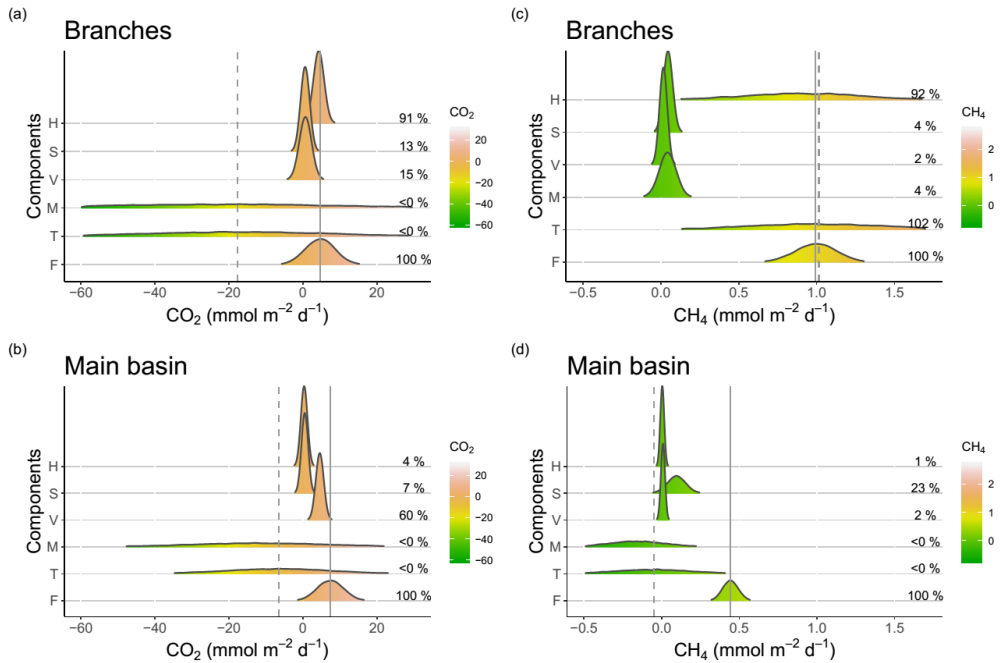


Figure 3: Density distributions of the different components of CO₂ (a, b) and CH₄ (c, d) surface budgets in the reservoir branches (a, c) and main basin (b, d). Components are: H = horizontal flow inputs, S = sediment inputs, V = vertical inputs, M = net metabolism (average of the incubation and diel O₂ monitoring methods), T = sum of all estimated sources and processes in the surface layer, and F = measured surface fluxes). Density curves are based on simulated normal distributions using the mean and standard error of each component. The x-axes and color scales represent the areal rate of CO₂ / CH₄. Mean values of the fraction of each component (in %) relative to the mean surface flux (F) are reported on the right side in each panel. The color scale represents the percentage of the mean surface flux accounted by each component. The solid and dashed grey lines represent the means of F and T respectively.

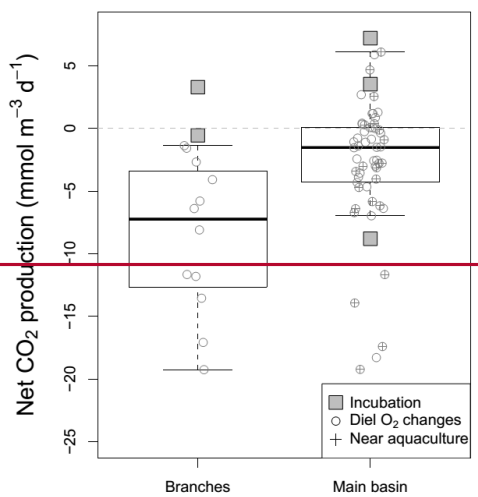
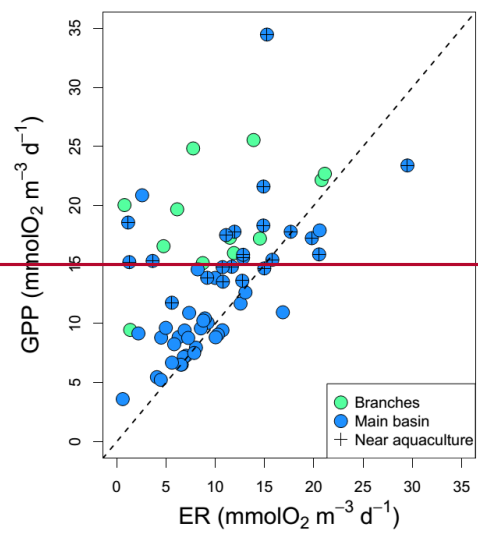
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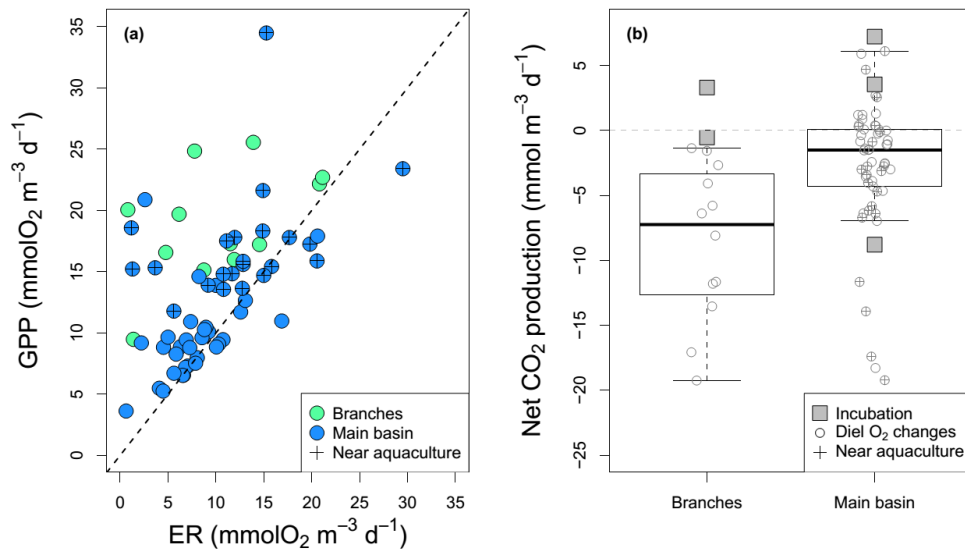
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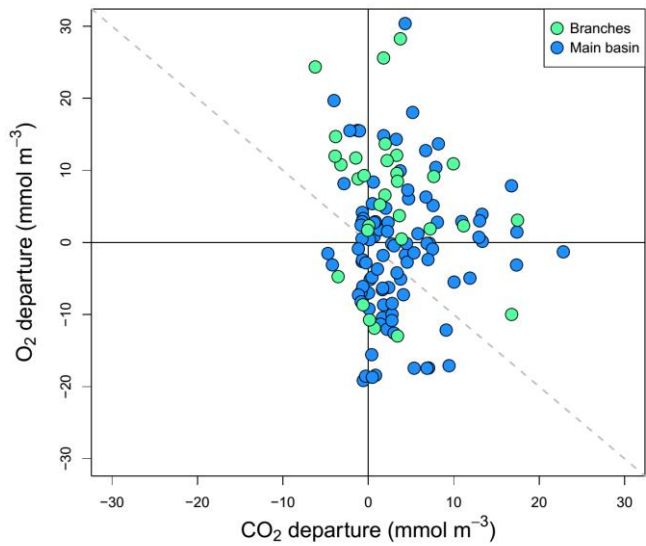
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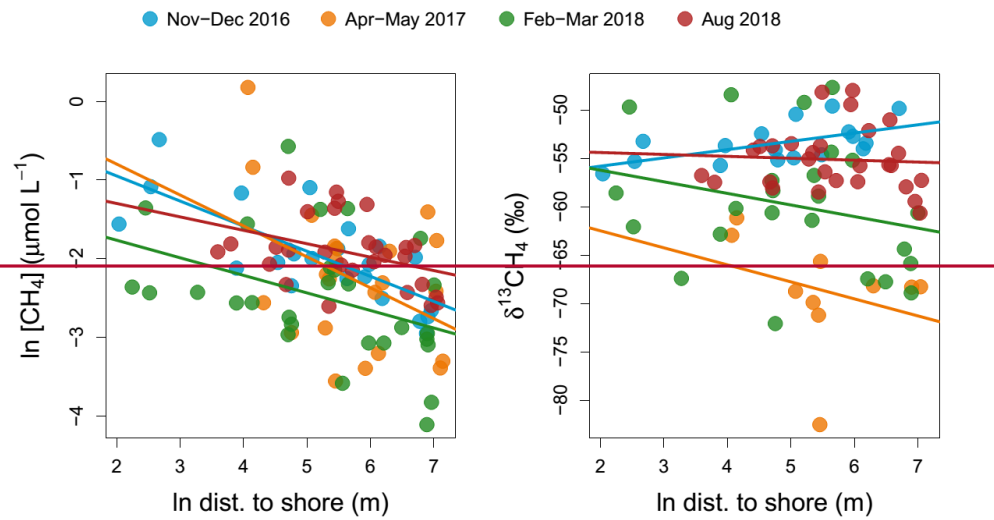


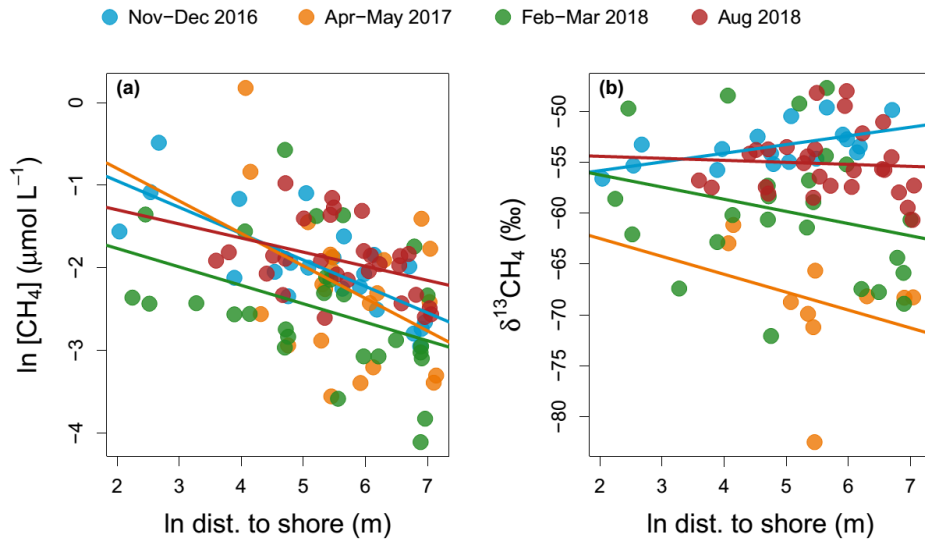


825 Figure 4: Epilimnetic daily GPP versus ER rates (left panel) derived from diel O_2 changes in the reservoir branches and main basin (including sites near aquacultures), with the 1:1 line (dotted). Panel (b) shows boxplots of the corresponding rates of CO_2 NEP (right panel) in the branches and main basin, with boxes bounds, whiskers, solid line, and open circles, and squares representing the 25th and 75th percentiles, the 10th and 90th percentiles, the median, single data points (diel O_2 method), and incubation derived rates respectively.



830 **Figure 5: Surface O₂ versus CO₂ departure from saturation for all sampled surface sites in the reservoir main basin and branches across all sampling campaigns.**





835 **Figure 6: Regression of CH₄ concentration (left panel) and isotopic signature (right panel) as a function of distance to shore in each sampling campaign in the main reservoir basin. For CH₄ concentration, regressions lines have the following statistics in order of sampling: p-values: < 0.001, 0.06, 0.03, 0.05, and R²_{adj}: 0.54, 0.13, 0.11. For δ¹³CH₄, all regressions had p-values > 0.2 except for the Nov-Dec 2016 campaign with p-value = 0.01 and R²_{adj} = 0.29.**