## Authors' response to Dr. Ji-Hyung

We thank Dr. Ji-Hyung Park for his very helpful and detailed comments on scientific and technical aspects of the manuscript. We modified the new version of the manuscript accordingly and hope it is now clearer and more complete.

The following color code is used to structure the text below:

- *Referee comment*
- Authors' response
- Changes to the manuscript

## Major comments

*Terms and methods of four pathways. This study compared four major pathways for GHG emissions. While this is a strength of this manuscript, authors did not pay enough attention to providing clear definitions and methodological details on the GHG fluxes associated with the four pathways. - First, it would be a good idea to define each pathway at its first use and use the term consistently. For instance, authors use diffusion or diffusive flux interchangeably, but I wondered if these terms were used to represent the flux associated with evasion or outgassing (more common terms in the literature). If authors opt for common terms and provide references wherever the terms are defined at their first use, the results of this manuscript could be more easily compared with other studies.*

Thank you for noting that, we agree with the importance of well defining the key terms used in the manuscript. We provided a clearer definition of the GHG emission pathways in the introduction: "Moreover, reservoirs can emit GHG through several pathways: diffusion of gas at the air-water interface (surface diffusion), release of gas bubbles formed in the sediments (ebullition), and for some reservoirs (mostly hydroelectric) through gas release following pressure drop upon water discharge (degassing), and through evasion of the remaining excess gas in the outflow river (downstream emissions).". We also added a sentence to define the pathways at the start of each method paragraph describing pathway measurements: *"Surface diffusion is the flux of gas between the water surface and the air driven by a gradient in gas partial pressure.", "Ebullition is the process through which gas bubbles formed in the sediments rise through the water column and are released to the atmosphere.", "Degassing of $CO_2$ and $CH_4$ right after water discharge, and downstream emissions of the remaining reservoir-derived $CO_2$ and $CH_4$ in the outflow river".*

We also homogenized the used of "surface diffusion" throughout the text and avoided the term "diffusive flux" for more consistency. Although the use of "evasion" or "outgassing" is common in the literature, we preferred in our case the term diffusion (also common in reservoir GHG studies) because it includes not only positive but also negative fluxes (uptake of $CO_2$, from the atmosphere to the water) which were occasionally observed in our measurements.

*Second, it is quite difficult to understand how authors quantified downstream emissions (L 137-). It looks like that authors are dealing with two separate processes (downstream emission and degassing). Please make it clear by using an appropriate subtitle and equations specifying each separate process in the relevant methods section. If my understanding is correct, degassing at the turbine may refer to the flux associated with the concentration difference across the dam. If downstream emission occurs as the next step following dam discharge, the flux calculation should take the concentration at discharge point, not Cup (gas concentration upstream of dam), as the entry point.*

We agree that the description of methods for degassing and downstream emissions are confusing, hence we renamed the method section 2.5" and reformulated the paragraph and associated equations to avoid confusion:

## "2.5 Degassing, downstream emissions and $CH_4$ oxidation

Degassing of $CO_2$ and $CH_4$ right after water discharge ($F_{deg}$), and downstream emissions of the remaining reservoir-derived GHGs in the outflow river ($F_{dwn}$) were calculated using the following Eq. (5) and Eq. (6):

$$F_{deg} = Q\left(C_{up} - C_0\right), \tag{5}$$

$$F_{dwn} = Q\left(C_0 - C_{19} + C_{ox}\right), \tag{6}$$

where $Q$ is the water discharge, and $C_{up}$, $C_0$ and $C_{19}$ the measured gas concentrations upstream of the dam at the water withdrawal depth, at the powerhouse right after water discharge, and in the outflow 19 km downstream of the dam respectively. $C_{ox}$ is the net change in gas concentration due to oxidation (loss for $CH_4$ and gain for $CO_2$). For downstream emissions, we considered that, after a river stretch of 19 km, all excess gas originating from the reservoir was evaded and gas concentration was representative of the outflow river baseline. This assumption potentially underestimates actual downstream emissions (in case of remaining excess gas after 19 km). However, given the observed exponential decrease of gas concentration along the outflow (Figure 3), emissions after 19 km are expected to be small compared to those in the 0 to 19 km river stretch, consistent with observations in other reservoirs (Guérin et al., 2006; Kemenes et al., 2007).

Gas concentrations upstream and downstream of the dam were obtained by measuring, in each campaign, $CO_2$ and $CH_4$ concentrations in a vertical profile right upstream of the dam at a 1 to 3 m interval from 0 to 32 m, and at four locations in the outflow: at 0 (power house), 0.6, 2.7, and 19 km downstream of the dam (Figure 1). Sampling was done using a multi-parameter probe equipped with depth, oxygen, and temperature sensors (Yellow Spring Instruments, YSI model 600XLM-M) attached to a 12 Volt submersible Tornado pump (Proactive Environmental Products) for water collection. Gas concentration and $\delta^{13}C$ were measured as described in section 2.3. Water withdrawal depth ranged from 20 to 23 m and was estimated based on known values of elevations of water intake and water level compared to sea level. Gas concentration in the water exiting the reservoir was defined as the average measured gas concentrations in the ± 1 m range of the withdrawal depth."

The idea behind the natural river baseline was to represent the state of the river and its gas emission without the excess gas originating from the reservoir in order to distinguish between natural riverine emissions and downstream emissions attributable to the reservoir. However, we agree that using measured gas concentration 19 km downstream of the dam gives a good estimate of the river baseline. Using the 19 km downstream concentration value as an upper bound was based upon the idea that there could be still some excess gas from the reservoir at this location (although minimal) like it was previously observed in other reservoirs (Guérin et al., 2006; Kemenes et al., 2007). Hence, we originally took the surface of the reservoir as a lower bound for baseline riverine gas concentration as it was consistently much lower than the value 19 km downstream and it would be the outflow concentration if water withdrawal was from the reservoir surface as is the case for natural lakes. Although our previous approach was meant to be cautious by using a range of values, we agree that it created more confusion than clarity. Hence, we changed our approach and used only the value 19 km downstream of the dam as a baseline of gas concentration in the outflow. We changed section 2.5 of the methods accordingly (cited above) and discussed the potential underestimation of downstream emissions by this new approach. We also changed the values in the text and tables when applicable, however, not that this did not affect the interpretation of the results, discussion, or conclusions.

Following this suggestion, we separated section 2.6 into two paragraphs and developed the second paragraph further to add information on models structure and how they compare to each other:

"The estimated GHG emissions of Batang Ai based on measured data was compared to values derived from the G-res model (UNESCO/IHA, 2017) and the model presented in Barros et al. (2011). Both models predict surface $CO_2$ and $CH_4$ diffusion as a function of age and account for the effect of temperature using however different proxies: the G-res uses effective temperature while Barros et al. model uses latitude (an indirect proxy that integrates other spatial differences). In terms of $CO_2$ surface diffusion, the G-res uses reservoir area, soil C content, and TP to quantify the effect of C inputs fueling $CO_2$ production, while Barros et al. model uses directly DOC inputs (based on in situ DOC concentration). For $CH_4$ surface diffusion, both models account for morphometry using the fraction of littoral area (G-res) or the mean depth (Barros et al. model). Overall, both models predict surface diffusion based on the same concptual framework but use different proxies. $CH_4$ ebullition and degassing are modeled only by the G-res, being the sole model available to this date. Details on models equations and input variables are presented in the Supplementary Information (Table S2 and S3)."

*Is this oligotrophic reservoir with very low DOC conc. common in the region? Please provide some regional background information about rivers and reservoirs as well as watershed information related to the reservoir nutritional status.*

In addition to the watershed description in the method section 2.1, we extended section 3.1 of the results and discussion to include additional information about watershed soils and regional comparison with other systems in terms of water chemistry:

"The oligotrophic status of the reservoir likely results from nutrient poor soils (Wasli et al., 2011) and a largely undisturbed forested catchment in the protected Batang Ai National Park. The reservoir's low Chla concentrations are comparable to the neighboring Bakun reservoir (Ling et al., 2017), and its DOC concentrations are on the low end of the wide range of measured values in nearby rivers (Martin et al., 2018)."

Following the above comment and the comment from reviewer #1, comparison with other systems was also added in the discussion (section 3.7) to better place Batang Ai characteristics in a regional and global context:

"The only three other sampled reservoirs in Southeast Asia (Nam Leuk and Nam Ngum in Lao PDR, and Palasari in Indonesia) also exhibited low organic C concentration (for reservoirs in Lao PDR) and low to negative average surface $CO_2$ diffusion despite their low latitude (Chanudet et al., 2011; Macklin et al., 2018). This suggests that, while additional data are needed, low $CO_2$ diffusion may be common in Southeast Asian reservoirs, and likely linked to the low organic C content."

"This may explain the unusually low DOC concentration in the reservoir and its inflows (0.3 to 1.8 mg $L^{-1}$, Table S1) that are among the lowest reported in freshwaters globally (Sobek et al., 2007). Clay-rich soils are ubiquitous in tropical landscapes (especially in Southeast Asia, Central America, and Central and Eastern Africa) (ISRIC - World Soil Information, 2019), however, their impact on global-scale patterns of aquatic DOC remains unknown. This may be due to a lack of aquatic DOC data, with the most recently published global study on the subject featuring only one tropical system and a heavy bias towards North America and Europe (Sobek et al., 2007). Exploring the global-scale picture of aquatic DOC and its link to watershed soils characteristics would be a significant step forward in the modeling of reservoir $CO_2$ diffusion."

*Two inflowing rivers and the outflowing river are indicated by names, but not shown on Fig. 1. Please show at least the reach included in your "downstream emission" calculation on the map.*

Figure 1 was altered to show inflowing rivers and sampling points downstream of the dam.
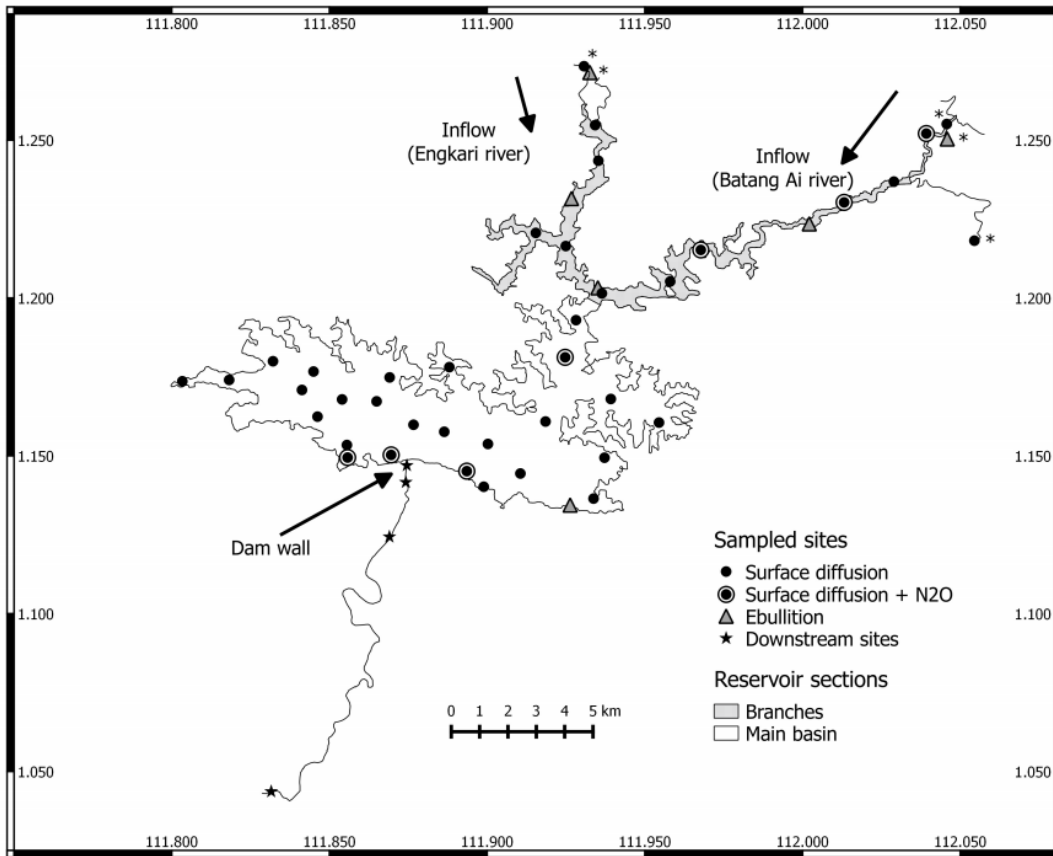
**Figure 1: Map of Batang Ai showing the location of sampled sites and reservoir sections. * Represents the reservoir inflow sites.**

*It is also missing in section 2.2. how and where you collected water samples.*

We reformulated the first sentence of section 2.2 to indicate more clearly how and where samples were collected:

"Samples for DOC, total phosphorus (TP), total nitrogen (TN), and chlorophyll a (Chla) analyses were collected from the water surface (<0.5 m) at all surface diffusion sampling sites shown in Figure 1 and during each campaign."

*Please also check the accuracy of the provided instrument information (for instance, Total Organic Carbon analyser 1010-OI?). The measurement of "Chl a" could be cited by a relevant reference, if you don't want to go into detail. There is no QC information about not only water analysis but also gas concentration and isotope analysis. For example, did you confirm the accuracy of CRDS measurements (L113) by using any certified standard gases? You also need to describe how you used CRDS for individual samples (not in continuous measurement mode).*

Methodological specifications on laboratory analyses were added in section 2.2 (water chemistry) and in section 2.3 (gas concentration and isotopic signature):

"TP was measured by spectrophotometry using the standard molybdenum blue method after persulphate digestion at 121ºC for 20 min, and a calibration with standard solutions from 10 to 100 µg $L^{-1}$ with a 5 % precision (Wetzel and Likens, 2000). TN analyses were performed by alkaline persulphate digestion to $NO_3$, subsequently measured on a flow Alpkem analyzer (OI Analytical Flow Solution 3100) calibrated with standard solutions from 0.05 to 2 mg $L^{-1}$ with a 5 % precision (Patton and Kryskalla, 2003). Water filtered at 0.45 µm was used for DOC analysis with a Total Organic Carbon analyser 1010-OI following sodium persulphate digestion, and calibrated with standard solutions from 1 to 20 mg $L^{-1}$ with a 5 % precision (detection limit of 0.1 mg $L^{-1}$). Chla was analysed through spectrophotometry following filtration on Whatman (GF/F) filters and extraction by hot 90 % ethanol solution (Sartory and Grobbelaar, 1984)."

"Three analytical replicates and a local sample of ambient air were taken at each site and analysed by gas chromatography using a Shimadzu GC-2040, with a Poropaq Q column to separate gases and an ECD detector calibrated with 0.3, 1, and 3 ppm of $N_2O$ certified standard gas."

"The gas phase was then injected in a 12 mL air-tight pre-evacuated vial and subsequently analysed through manual injection on a Shimadzu GC-8A Gas chromatograph with flame ionization detector following a calibration curve with certified gas standards (0-10000 ppm for $CO_2$ and 0-50000 ppm for $CH_4$). The samples were also analyzed for isotopic $\delta^{13}CO_2$ and $\delta^{13}CH_4$ signatures by manually injecting 18 mL of gas in a Cavity Ring Down Spectrometer (CRDS) equipped with a Small Sample Isotopic Module (SSIM A0314, Picarro G2201-i Analyzer) set in a non-continuous mode with a three point calibration curve based on certified gas standards (-40 - 3.9, and 25.3 ‰ for $\delta^{13}CO_2$, and -66.5, -38.3, -23.9 ‰ for $\delta^{13}CH_4$)."


**Minor comments**

*L132: lower "bounds"?*

The sentence was changed

*L171: something wrong with TP and TN values (probably with TN unit).*

This was fixed, thank you for noting it!

*L220-221 "δ13CH4 steadily increased indicating riverine CH4 oxidation": What about the effect of gas evasion? Please cite relevant references to explain why δ13CH4 changed.*


We agree that this is an important point to develop in the discussion, and we therefore added a sentence to mention that gas evasion has a very small fractionation factor compared to $CH_4$ oxidation (an order of magnitude lower). We also added three references in the text to support our interpretation.

"Along the outflow river, $CO_2$ and $CH_4$ concentrations gradually decreased, $\delta^{13}CO_2$ remained stable, whereas $\delta^{13}CH_4$ steadily increased (Figure 3). Given the very small isotopic fractionation (0.9992) of $CH_4$ during gas evasion (Knox et al., 1992), the only process that can explain the observed $\delta^{13}CH_4$ increase is $CH_4$ oxidation (Bastviken et al., 2002; Thottathil et al., 2018)."

*L229: there might be more studies; for instance, refer to DelSontro et al. 2016 (Limnol. Oceanogr. 61: S188) though their dam was a ROR.*

Thank you for noting that. DelSontro et al. 2016 did not directly estimate $CH_4$ oxidation but they explicitly incorporate it in their mass balance, and we agree that their paper is worth citing for in this context. We changed the sentence to include it:

"Despite having a measurable impact on reservoir GHG emissions, $CH_4$ oxidation downstream of dams was only considered in three other reservoirs to our knowledge (DelSontro et al., 2016; Guérin and Abril, 2007; Kemenes et al., 2007)."

*L333-334 "withdrawal depth decrease": this must be "increase", right?*

The sentence was change to: "shallower water withdrawal"

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