The authors thank the reviewer for her/his positive comments on our work and for her/his constructive remarks

The manuscript presented results of a study carried out on carbon dioxide emissions from the Nam Theum 2 Reservoir in the Mekong River watershed in Laos. The major focus has been on the influence of Dam and commissioning of a power plant. Their study clearly shows the impact of human interference on the natural flow systems and processes on carbon dioxide system and its emissions. The authors deserve compli- ments for their meticulous planning of their experiments and strategic location of sam- pling sites. Results are presented and discussed adequately and I do not have any major comments. The following three minor points may help the authors in contributing to the clarity.

1. Please define 'drawdown area' in introduction.
The following lines were added in the introduction: "In some reservoirs with large water level variations, large surface areas of soils known as drawdown zones are periodically exposed to the atmosphere (for example, Three- Gorges and Nam Theun 2 reservoirs)."

2. Caption for Figure 5 needs a re- vision
The extra (a) label was removed from the caption

and 3. The influence of freshwater discharge on distributions of carbon param- eters in the studied hydrological regime has not been explicitly presented. A strategy showing the river discharge variations in relation to changes in carbon dioxide proper- ties in reservoir and drawdown area might help explain "We confirm the importance of the flooded stock of organic matter as a source of C fuelling emissions and we show that the drawdown area contributes, depending on the year, from 50% to 75% of total annual gross emissions in this flat and shallow reservoir (lines 47-50)."

The large variation of the contribution of the drawdown zone do not result from hydrological variations since emissions from the drawdown zone are constant throughout the years. The following sentence was added in order to clarify: "Since the CO_2 emissions from the drawdown zone are almost constant throughout the years, the large interannual variations result from the significant decrease of diffusive fluxes and downstream emissions between 2010 and 2013."

The authors thank the reviewer for his thorough review of the manuscript

General: The contribution of global freshwater reservoirs to the atmospheric CO2 is an important problem. Although the storage bodies, the reservoirs proper have been examined in reasonable detail, emissions in the downstream regions adjacent to the dams in the flow paths have not been addressed sufficiently. In this background, the present paper is welcome. The authors previously published in the same journal (Biogeosciences) on CH4 emissions, as 2 papers, the first one dealing with downstream stations (Deshmukh et al., 2016) and the second dealing with the reservoir proper (Guerin et al., 2016). This MS is on CO2 emissions for the combined area. The experimental work is solid strong and data of high quality. However, after reading their 2 papers also (along with the present), the sampling protocol, flux calculations and discussion of results are much the same. The readers would be justified to expect from this paper not just about concentrations and fluxes of CO2, but a critical appraisal, in particular differences between CH4 and CO2 and a geochemical reasoning in terms of the processes / geochemistry. To a reader with taste for science, the Results and Discussion appeared routine, unnecessarily long and repetitive. The authors, during discussion (L. 553/557) did briefly mention about the differences in concentration trends of CH4 and CO2 but did not go further as to explain the processes except to mention that higher solubilization of CO2 leads to higher concentration.

We have already published 5 papers on CH4 emissions from Nam Theun 2 Reservoir (see below) and we do not feel that new discussion on CH4 is necessary. The present manuscript focuses on CO2 emissions from the major known pathways and we demonstrate for the first time the existence of an overlooked pathway i.e. the drawdown area, which constitutes, in our opinion, a significant result worth a stand-alone paper.

Descloux, S., V. Chanudet, B. Taquet, W. Rode, P. Guédant, D. Serça, C. Deshmukh and F. Guérin (2016). "Efficiency of the Nam Theun 2 hydraulic structures on water aeration and methane degassing." Hydroécol. Appl. 19: 63-86.

Deshmukh, C., F. Guérin, D. Labat, S. Pighini, A. Vongkhamsao, P. Guédant, W. Rode, A. Godon, V. Chanudet, S. Descloux and D. Serça (2016). "Low methane (CH4) emissions downstream of a monomictic subtropical hydroelectric reservoir (Nam Theun 2, Lao PDR)." Biogeosciences 13(6): 1919-1932.

Deshmukh, C., D. Serca, C. Delon, R. Tardif, M. Demarty, C. Jarnot, Y. Meyerfeld, V. Chanudet, P. Guedant, W. Rode, S. Descloux and F. Guérin (2014). "Physical controls on CH4 emissions from a newly flooded subtropical freshwater hydroelectric reservoir: Nam Theun 2." Biogeosciences 11(15): 4251-4269.

Guérin, F., C. Deshmukh, D. Labat, S. Pighini, A. Vongkhamsao, P. Guédant, W. Rode, A. Godon, V. Chanudet, S. Descloux and D. Serça (2016). "Effect of sporadic destratification, seasonal overturn, and artificial mixing on CH4 emissions from a subtropical hydroelectric reservoir." Biogeosciences 13(12): 3647-3663.

Serça, D., C. Deshmukh, S. Pighini, P. Oudone, A. Vongkhamsao, P. Guédant, W. Rode, A. Godon, V. Chanudet, S. Descloux and F. Guérin (2016). "Nam Theun 2 Reservoir four years after commissioning: significance of drawdown methane emissions and other pathways." Hydroécol. Appl. 19: 119-146.

CO2 indeed provides a greater opportunity to discuss its more complex environmental response than CH4. CO2 is a reactive gas, unlike CH4 which undergoes only physical dissolution. CO2's re- action with water produces HCO3- , CO32-, H2CO3 in addition to physically dissolved CO2(aq) species all of which inter-convert as part of the carbonate equilibria. Due to the pH dependence of their inter-conversion, CO2(aq) and HCO3- are ~ 50% each at pH 6 while at pH 10, HCO3- and CO32- are ~50% each. At lower pH, degassing is favoured which happens in 2 cases, (i) seasonally in winter when the reservoir expe- riences overturning and (ii) spatially at the reservoir station 9 where mixing with the low pH deepwater takes place. The pH which varied significantly – in different ranges at different

stations / regions may be reflecting these processes. In the reservoir and at various other water stations pH varied significantly. For example, at reservoir sur- face, the range was 5.21 - 8.76 (L. 271) when the corresponding share of CO2(aq) in the CO2 system is >80% and ~ 10% respectively, and the former situation is a hugely favourable CO2 emission condition. Post degassing, pH should be expected to in- crease at surface (up to the limit of neutral pH). But the higher limit of pH which was on the alkaline side (pH>7) shows that there are cations (from dissolved minerals) e.g., Na+, K+ etc whether derived naturally or anthropogenically. In addition to CO2 (aq), authors measured TIC, but they did not explore CO2 emission in relation to the TIC-CO2(aq) equilibrium leading to the basic question as to why they presented the latter data.

As in the majority of lakes and reservoirs, CO2 in produced throughout the water column by aerobic or anaerobic respiration and is partly consumed in the euphotic zone by primary production. Mineralization of organic matter through bacterial activity lead to CO2 production which acidifies the environment and to direct production of protons while consumption of CO2 by primary production increase the pH of surface water during productive periods. This is classical vertical profiles of pH in such environments.
TIC results are mostly used for the carbon mass balance and the comparison of total input from the watershed with the total export downstream and emissions to the atmosphere. This comparison is the basis of the section 4.3 in the discussion. As TIC dominates the carbon inputs to the reservoir, it is a key element of the article.

Discussion of Figs. 2 and 3 is absent except for a brief mention of the relative quantities / fluxes of DOC, POC and TIC.
The figure 2 depict raw data (TIC, DOC, POC, CO2) in all rivers from the Nam Theun watershed that were used for the calculation of carbon inputs from the Nam Theun watershed presented in figure 3.
The section 4.3 on the source of carbon fuelling emissions in the NT2 reservoir is based on the comparison of figure 3 showing the carbon inputs from the watershed and the figure 8 showing emissions from the NT2 reservoir. As mentioned above, carbon inputs from the watershed are key elements of the mass balance and discussion.

For CO2 and TIC determination, authors gave citations of their earlier works. It would be useful if the methods are explained in brief.
The headspace method used for CO2 measurements is well known and the name of the method is self-explicit (eg, Guérin et al., 2006). TIC, DOC, TOC measurements are routine measurements with a TOC analyser from shimadzu as done in numerous published studies. We believe the description made in the article for the sample preparation and analysis is detailed enough.

Production and accumulation of CO2: Authors have not explained how. Using water residence time and vertical stratification index authors explained in their papers (e.g. Guerin et al., 2016). They also could relate CO2 production (by the metabolism of organic matter of sediments and water column by bacteria) and accumulation to age. The deep water is more aged than the surface water, and in it CO2 accumulated over longer periods also resulting in lower pH. The detailed hydrology and minor variations in concentrations should all fall in

pattern if this were done. Thus, authors have to better consider a process-oriented description of their results rather than a just presentation of concentrations and fluxes.
The authors do not understand the point raised by the reviewer. The surface water is less concentrated in CO2 and has a higher pH because of primary production and loss of CO2 by emissions. The water in the reservoir comes from the watershed and difference in age between surface and bottom water are not expected in a reservoir. Some parts of reservoir experiences longer residence time than other parts, and this is places where CO2 concentration are higher (see L546-548) We observed slightly lower pH, but these differences were not significant..

Further comments:
General:
1. The CO2 concentrations (Text e.g., L. 394, 396, 428 etc.) and emissions (Table 3) are given in grams. The standard method is to give them in terms of CO2-C. The values would then be down by a factor of 44/12 i.e., 3.67.
There is no official recommendation for Biogeosciences. There are as many published studies reporting fluxes in gC-CO2 as fluxes in gCO2. We kept our data in gCO2.

2. Please give a space after semicolon (;) for all multiple citations.
The absence of space is due to the use of the Endnote software. This would be solved during the manuscript processing

3. L. 73: drawdown emissions: To my understanding, draw-down is opposite of emission. The former is from atmosphere to surface water when surface water is under-saturated (this is promoted by primary production) and the latter is from the surface water to the atmosphere in case of surface super-saturation (this is promoted by winter convection, which you are calling as reservoir overturning). There is no mention of drawdown emissions in for example Chen et al., 2009 cited by you. Do you mean emission in the drawdown area i.e., the reservoir or river area where the water level is lowered due to the construction of the reservoir? If so, the drawdown emissions should be replaced with emission in drawdown area throughout the MS.
It seems that the reviewer is not familiar about what is a drawdown area in a reservoir. This term is widely spread nowadays in the framework of GHG emissions from hydroelectric reservoirs studies. As an example, the paper by Chen et al 2009 is namely focused in that very precise point as illustrated in the title: *“Chen, H., Y. Wu, X. Yuan, Y. Gao, N. Wu and D. Zhu (2009). "Methane emissions from newly created marshes in the drawdown area of the Three Gorges Reservoir." J. Geophys. Res. 114: D18301.”*
We do not understand what the reviewer is refering to when he writes that "the creation of a reservoir would lower the water level in the area".
Since the focus of our paper is on the drawdown area of a monomictic reservoir (a reservoir which overturn once a year), we hardly see how the reviewer's comment can be considered as relevant.

4. Often, the results are specific to only the study area, and not applicable as a general phenomenon which makes the reading less involving for the reader. Hence, the authors better discuss critically their results focusing on (i) similarities and (ii) differences with other

similar reservoirs. In the Discussion section, attention may be paid to spatial differences and seasonal differences in sub-sections.
Results are by definition specific to the area. We always bring comparison with other sites as it can be seen in almost all paragraphs of the discussion. Last paragraph of each section attempts to generalise the results to other sites or climatic zones whenever it is relevant.

5. Fig. 8a constitutes the core result, and instead of waiting till the end of discussion, this figure may be brought to Results section, and later discussed critically (in the light of relevant comments below).
The Fig 8 cannot be shown before all individual terms of emissions are described and discussed in details in terms of spatial and temporal variability in the result section. It makes sense that the figure 8, which is the synthesis of all results, is referred to in the discussion section where it is commented in details.

6. A significant part of discussion draws on CH4 distribution, but a direct comparison of the two results is not made. The drawdown area is an important source of CH4
CH4 is cited 9 times in the discussion and conclusion which correspond to 9 pages, it is therefore not a significant part of the discussion and as mentioned in our first comment, our CH4 dataset is published in a 5 papers and does not deserve more attention, specially in a paper focusing on specific pathway for CO2.
We clearly demonstrated in Serca et al., 2016 that the drawdown area of this reservoir is not a significant source of CH4 (3% of total emissions).

7. Let me also give my opinion on the Title: As commented above, emissions from the drawdown area are significant only during the warm season when the drawdown area is exposed with fall in water level. Moreover, there is a gradual fall in these emissions too. Perhaps, if the dam were visited in 2017, the emissions may be expected to be further low, which is also mentioned by authors (L. 61-61 and 632-634). Hence, it may be misleading to say that drawdown areas are a neglected pathway to the atmosphere.
Based on common definition of drawdown zone, this title clearly justifies the outcomes of this research work.. According to Abril et al. (2005) at Petit Saut, total emissions (disregarding drawdown emissions which were not measured) were 9 to 6 times higher than carbon inputs from the watershed during the first 4 years for similar carbon inputs which indicates a faster decrease of emissions in NT2R than at Petit Saut. This sharp decrease of emissions at NT2R might be due to the fact that the flooded pool of OM and therefore the amount of labile OM in NT2R was twice smaller than the amount of OM flooded in the Petit Saut (Guérin et al., 2008;Descloux et al., 2011).

8. Interestingly, CH4 emission also took place during the dry season and the authors (Deshmukh et al., 2016) explained it to be due to intermittent exposure (and inundation) when anoxic (and oxic) conditions prevailed. Perhaps this point in itself would suggest the need for a direct comparison of the CO2 and CH4 results.
Deshmukh et al (2016) deals with downstream emissions and not with drawdown area as the reviewer understood.

Specific:
L. 35: Pl. include in Laos PDR before in the Mekong River water shed.

Lao PDR was added

L. 39-40: Where are the river stations (Nam Theun watershed) in Fig. 1? Should there be a comma after Nam Theun water- shed in Line 40?
Pristine was added to the sentence for consistency with the Fig 1 caption and a coma was added

L. 40: Nine: Change to 9 for consistency.
Numbers were changed

L. 44: in 2012-2013: Pl. change to during 2013-2013, as monitoring was done in both years.
Changed to in 2012 and 2013

L. 77: Pl. add in China before the citation.
added

L. 104: decreased down to 107 km2: from what area? Is it about 500 km2?
Changed by "ranged seasonally between 489 in the WW season to 170 km^2 in the WD season during the course of the study."

L. 107: m3s-2: This is not a correct unit for discharge. Later you mentioned m3s-1 which is right.
Typo corrected

L. 123-125: besides the hydrology details which were already described in Guerin et l. (2016), it would be good if you can give depths of the stations also.
Hydrology and depth were given in Guerin et al (2016) as it was mandatory information for the understanding of the spatial variation. As we would have to give ranges, the addition of hydrology and depth details would impair the readability of the discussion without providing any substantial clarification or useful information..

L. 159: What is specific water discharge?
Done

L. 197: soils types: Pl. correct to soil types
Done

L. 199: details: Pl. use singular (detail) as above. And pl. make similar corrections elsewhere also.
Done

L. 199: Table 1 – what is interm. for?
Rewritten as follow ("interm.up" and "interm.down" samples, with interm standing for intermediate)

L. 213: One of the subsample: Pl. correct it as one of the subsamples (Pl. compare with the above two corrections).

done

L. 221: What is specific water discharge? What is Hum?
As those lines refer to the description of the soil static chamber, we do not understand the comment. Elsewhere in the MS, 'Hum' might refer to humidity.

L. 236: In Fig. 2, it would be better if the data are provided for the area classification followed in Fig. 8.
We are puzzled by this comment. Fig 2 reports particulate and dissolved inputs from the main pristine tributaries of the reservoir when Fig 8 reports GHG emissions from the reservoir itself and all impacted area.

L. 255 (also L. 638): This data has not been critically discussed.
The paper includes TIC, and TOC as they are needed for providing a carbon mass balance to identify the source of carbon fuelling CO2 emissions, however the focus of the paper is on CO2 emissions to the atmosphere. Furthermore, a detailed discussion on carbonate chemistry would require high precision pH data that we do not have to calculate equilibrium.

L. 259: This figure is illegible. The trends are not clearly seen due to the problem of scaling of the X-axis.
In order to be able to observe seasonal variations, the same scale is used whatever the season. The scale was adapted for each site to improve readability

L. 300: Are 70% and 56% (for 2011 and 2010 & 2012) annual average O2 saturation values or seasonal values? Pl. clarify. Pl. modify text for better clarity.
"On average" was added for both cases, referring to annual calculation for 2011 and for the years 2010&2012

L. 301: the is a repetition.
removed

L. 325: From March to August: You have referred so far to seasons. Better be consistent and refer as WD and WW seasons.
March to August encompass the second half of the WD season and the first half of the WW season, therefore referring to season would not depict reality. Therefore, giving the precise months was here the most accurate way.

L. 332: space between five and fold.
Done

L. 338: Pl. change a to an.
Done

L. 337-340: Why was this? Pl. explain in Discussion.
It is already explained here L524-526. As found for CH4, the main factor influencing the spatial variability of CO2 in the water column is the vertical mixing of the water column induced by the water intake located close to RES9 (Deshmukh et al., 2016;Guérin et al.,

2016). The design of the water intake enhances horizontal water current velocities and vertical mixing which lead to the transport of bottom waters to the surface. As a consequence, surface concentrations at RES9 were up to 30 times higher than at other stations in 2010 and 2011 (Figure 5b).

L. 342: Pl. use on instead of to.
Done

L. 344: Figure 5e: These are also the trends shown in 5c. Suggest removing. Suggest removing 5f also as this data is given in Table 3 (column 3).
Panel 5c provides average diffusive fluxes of CO2 in mmol m-2 d-1 at the stations RES1-8 while the panel 5e shows total diffusive emissions at the stations RES1-8 + RES9 in GgCO2 month-1 showing the relative importance of RES9 in the total diffusive emissions. Those data are not shown in table 3. Similarly, the panel f includes information from RES9 not given in table 3

L. 390: -32-33762: Pl. clarify the hyphen. The first hyphen seems to be a negative sign and the latter for range.
Done

L. 391: (not shown): The data can be included in Figure 5 as replacements for 5e and 5f to be deleted (see an earlier comment).
The figure 5 is about fluxes at the reservoir surface while the data on L391 are from the channel downstream of the powerhouse

L. 401: Fig. 6b: This data are included in Table 3 (column 5). Pl. remove.
What is the problem of citing in the text values included in a table?

L. 419: Where is Figure 6d?
Typo: fig 6b

L. 424-425: no bubbles was ever observed for depth higher than 16 m: Pl. delete text as this was given in Methods section.
Reworded as follow: The CO2 content in the sampled bubbles was 0.29±0.37% (n=2334). On average, the CO2 bubbling was 0.16 ± 0.24 mmol m-2 d-1 (0-2.8 mmol m-2 d-1) for depth shallower than 16m.

L. 434: stagnic property: Pl. explain briefly what a stagnic property is.
This is the classic term of pedology which is defined by the International soil classification system meaning that the soil was flooded. “stagnic properties: saturated with surface water (or intruding liquids), at least temporarily, long enough that reducing conditions occur”

L. 439-440: surface moisture ranging from 17.5 to 51.2% and temperature ranging from 18.1 to 34.2◦C (Table 2): For consistency, pl. change text as: surface moisture (17.5 - 51.2%) and temperature (18.1 -34.2◦C) (Table 2).
done

L. 443: This p value of 0.452 is not significant! Is it a typo?
Typo, 0.0452

L. 443-445: This sentence is not self-explanatory.
Rephrased as follow: Since we did not observe significant spatial variations related to topography, humidity or temperature that could have been considered for refine spatial and temporal extrapolation, we further consider the average of all fluxes that is 279±27 mmol m-2 d-1 throughout the years.

L. 449: could reach: For consistency, pl. change to reached.
Replaced by have reached

L. 450, 451: Pl. change changes to changed.
Done for reaches/reached

L. 454-455: Fig. 7 indicates that 2012 emissions were higher as July and August were also CO2-emitting. Pl. explain why under Discussion.
Modified as follow: Around 80-90% of the annual emissions occurred within 4-6 months of transition period between the WD and WW seasons (Figure 7) when the drawdown area surface is at its maximum

L. 473-475: This sentence is a repetition of the earlier sentence in content.
The two sentences were combined as follow: However, no CO_2 burst was observed at the beginning of the CD season evidencing that reservoir overturn has only a moderate impact on CO_2 emissions.

L. 475: This assumption is reinforce: Pl. correct to This assumption is reinforced
Done

L. 475: hot moments: When were those hot moments and why?
The CH4 emission dynamic depending on burst of emissions during overturn, and often called hot moments, is described in Guerin et al. (2016). Any detailed description on this phenomenon is beyond the scope of the manuscript under evaluation.

L. 477: the higher concentrations were observed: Pl. remove the definite article. Also, explain why.
Modified as follow: As observed in most tropical and subtropical reservoirs, the higher concentrations were observed during the warm seasons due to long residence time of water and warmer conditions enhancing CO2 build-up (Abril et al., 2005;Kemenes et al., 2011;Chanudet et al., 2011) whereas the lowest were found after reservoir overturn when the water outgassed (Chanudet et al., 2011).

L. 481: Pl. change the first of to a L. 482: change was observed nutrient concentrations: Correct to change was observed in nutrient concentrations.
done

L. 487-489: No, the quantity of autochthonous OM is not greater than phytoplankton primary production. Hence, there should be some other mechanism (source).
Inland waters are mostly heterotrophic which indicates that they "must receive significant inputs of organic carbon from adjacent ecosystems, assigning an important role to the lateral exchanges of carbon between land aquatic ecosystems (Duarte. and Prairie, 2005). Reservoirs are an extreme case since during the first years, most of the carbon is supposed to come from the flooded vegetation and soils (Abril et al., 2005, Guérin et al, 2008, Prairie et al., 2017 and this study)

Duarte, C. M. and Y. T. Prairie (2005). "Prevalence of heterotrophy and atmospheric CO2 emissions from aquatic ecosystems." Ecosystems 8(7): 862-870.
Prairie, Y. T., J. Alm, J. Beaulieu, N. Barros, T. Battin, J. Cole, P. del Giorgio, T. DelSontro, F. Guérin, A. Harby, J. Harrison, S. Mercier-Blais, D. Serça, S. Sobek and D. Vachon (2017). "Greenhouse Gas Emissions from Freshwater Reservoirs: What Does the Atmosphere See?" Ecosystems.,)

L. 498: older reservoir: Pl. change to older reservoirs.
done

Fig. 1: This figure is cluttered. The station codes are too long (and also not explained) and contribute to this clutter. What is the direction of river flow? What are NKT, TRC, DCH and XBF? The artificial channel is not marked properly in figure, and it is difficult to understand when mentioned e.g. in L. 530. Some terms included in legend e.g., Stream and downstream channel occur nowhere in text. Res 1 and downstream of reservoir – are they same? It should help the reader if you explained the provenance of different sampling stations in the Methods section, or as commented under Table 3.
Definition of all abbreviations are now given in the caption, the downstream channel is now better differentiated from rivers, arrows indicating the flow were added.

L. 549: For consistency, pl. change between the WD and the WW season (April – July).
done

L. 551: emissions factors: Pl. change to emission factors.
done

L. 552-557: This difference between CH4 (earlier work) and CO2 could be explored further.
Same explanation as before on the inclusion of CH4 in this article

L. 555: Table 3: Pl. give data separately for Res 9. This can be done by inserting a row after the header row for giving the stations included.
This is done in figure 5 already

L. 559: compare to most of the reservoirs: Pl. correct as compared to most of the reservoirs.
Done

L. 564-567: This sentence is a repetition from earlier discussed.

Compared to L541, the result of the overturn is added to the degassing at the water intake in order to explain the low downstream emission

L. 568: For consistency of tense, pl. change increase to increased.
Done

L. 568-569: This sentence is also a repetition (Pl. see the opening sentence of this Section!).
The opening sentence is on total emissions from the whole systems. Here, we are focusing on diffusive fluxes as clearly stated

L. 579: down to 7oC in air in March 2011: Was this given under Results?
It is included in the averages given in the site description

L. 620: were taking into: Pl. correct as were taken into
Done

L. 624: this study highlights: But this study is about CO2 only.
CH4 was removed

L. 688: Pl. correct algaes as algae
Done

L. 696: in a tropical reservoir: Pl. specify. Correct it as in the tropical NAM 2 reservoir.
This is the first study of its kind in a subtropical reservoir, therefore the statement is correct

L. 705: Pl. change all with different
Changed to “all known pathways”

L. 708-711: This sentence is redundant.
Redundant with which other sentence? As the conclusion is a place to put together all important findings of a study, the eventual redundancy is not, in our opinion, a problem.

L. 712: with time over the years: Pl. remove with time.
done

L. 713: represent: Pl. correct it to represents.
done

L. 715-717: But this is important only in the initial years after impoundment as evident in Fig. 8a. By the year 2013, the emissions have decreased significantly. Also, during the WW and particularly CD season, a seasonal shift of emissions happened and the reservoir emissions far surpassed the emissions from the drawdown area, thereby restoring the condition existed pre-power plant commissioning. Thus, the drawdown area and Reservoir have their own seasons when emissions peak – WD and the initial part of WW seasons in the former and the later part of WW season and CD season in the case of the latter. Pl. explain clearly under Discussion the result and why it is so.

The flooded biomass is the main source of carbon fuelling emissions, whatever the season and while permanently under water (high water level) or seasonally covered/uncovered (low water level). Emissions from the drawdown area obviously occur only at the low water level when the soils are not submerged.

L. 718-720: Although the % emissions from the drawdown area is 75% of total, in absolute terms, the emission (quantity) is same or perhaps less in 2013, as prior to commissioning.
Up to 75% was changed to 40-75%. Drawdown emissions is the only term which appears to be quite constant since the creation of the reservoir.

L. 729: footprint of the reservoir: What is footprint? Not discussed earlier under Discussion.
Reservoir footprint is the area of influence of the reservoir

Carbon dioxide emissions from the flat bottom and shallow Nam Theun 2 Reservoir: drawdown area as a neglected pathway to the atmosphere

Chandrashekhar Deshmukh[1,2,3,a], Frédéric Guérin[1,4,5], Axay Vongkhamsao[6], Sylvie Pighini[6,b], Phetdala Oudone[6,c], Saysoulinthone Sopraseuth[6], Aranud Godon[6,d], Wanidoporn Rode[6], Pierre Guédant[6], Priscia Oliva[1], Stéphane Audry[1], Cyril Zouiten[1], Corinne Galy-Lacaux[2], Henri Robain[7], Olivier Ribolzi[1], Arun Kansal[3], Vincent Chanudet[8], Stéphane Descloux[8], Dominique Serça[2]

[1]{Géosciences Environnement Toulouse (GET), Université de Toulouse (UPS), 14 Avenue E. Belin, F-31400 Toulouse, France}

[2]{Laboratoire d'Aérologie - Université de Toulouse - CNRS UMR 5560; 14 Av. Edouard Belin, F-31400, Toulouse, France}

[3]{Centre for Regulatory and Policy Research, TERI University, New Delhi, India}

[4]{IRD ; UR 234, GET ; 14 Avenue E. Belin, F-31400, Toulouse, France}

[5]{Departamento de Geoquimica, Universidade Federal Fluminense, Niteroi-RJ, Brasil}

[6]{Nam Theun 2 Power Company Limited (NTPC), Environment & Social Division – Water Quality and Biodiversity Dept.– Gnommalath Office, PO Box 5862, Vientiane, Lao PDR}

[7]{IRD, iEES-Paris, Centre IRD France-Nord, 32 avenue Henri Varagnat, 93143 Bondy Cedex, France}

[8]{Electricité de France, Hydro Engineering Centre, Sustainable Development Dpt, Savoie Technolac, F-73373 Le Bourget du Lac, France}

[a]{now at: Asia Pacific Resources International Limited (APRIL), Indonesia}

[b]{now at: Innsbruck University, Institute of Ecology, 15 Sternwartestrasse, A-6020 Innsbruck, Austria and Foundation Edmund Mach, FOXLAB-FEM, Via E. Mach 1, IT-38010 San Michele all'Adige, Italy}

[c]{now at: Department of Environmental Science, Faculty of Environmental Sciences, National University of Laos, Vientiane, Lao PDR}

[d]{now at: Arnaud Godon Company, 44 Route de Genas, Nomade Lyon, 69003 Lyon, France}

Correspondence to: F. Guérin (Frederic.guerin@ird.fr)

Abstract

Freshwater reservoirs are a significant source of CO_2 to the atmosphere. CO_2 is known to be emitted at the reservoir surface by diffusion at the air-water interface and downstream of dams or powerhouses by degassing and along the river course. In this study, we quantified total CO_2 emissions from the Nam Theun 2 Reservoir (Lao PDR) in the Mekong River watershed. The study started in May 2009, less than a year after flooding and just a few months after the maximum level was first reached and lasted until end of 2013. We tested the hypothesis that soils from the drawdown area would be a significant contributor to the total CO_2 emissions.

Total inorganic carbon, dissolved and particulate organic carbon and CO_2 concentrations were measured in 4 pristine rivers of the Nam Theun watershed, at 9 stations in the reservoir (vertical profiles) and at 16 stations downstream of the monomictic reservoir on a weekly to monthly basis. CO_2 bubbling was estimated during five field campaigns between 2009 and 2011 and on a weekly monitoring, covering water depths ranging from 0.4 to 16m and various types of flooded ecosystems in 2012 and 2013. Three field campaigns in 2010, 2011 and 2013 were dedicated to the soils description in 21 plots and the quantification of soil CO_2 emissions from the drawdown area. On this basis, we calculated total CO_2 emissions from the reservoir and carbon inputs from the tributaries. We confirm the importance of the flooded stock of organic matter as a source of C fuelling emissions. We show that the drawdown area contributes, depending on the year, from 40% to 75% of total annual gross emissions in this flat and shallow reservoir. Since the CO_2 emissions from the drawdown zone are almost constant throughout the years, the large interannual variations result from the significant decrease of diffusive fluxes and downstream emissions between 2010 and 2013. This overlooked pathway in terms of gross emissions would require an in-depth evaluation for the soil OM and vegetation dynamics to evaluate the actual contribution of this area in terms of net modification of gas exchange in the footprint of the reservoir, and how it could evolve in the future.

Supprimé: four

Supprimé: nine

Supprimé: -

Supprimé: and w

Supprimé: 50

Mis en forme : Indice

1 Introduction

Carbon dioxide (CO_2) emissions from inland waters were recently revisited and it appears that emissions from freshwater reservoirs contribute significantly despite the disproportionally small surface area of these systems (Barros et al., 2011;Raymond et al., 2013;Deemer et al., 2016). The CO_2 production and subsequent emissions in reservoirs result from the degradation of the flooded organic matter (OM) and the OM originating from the watershed (Galy-Lacaux et al., 1997b;Abril et al., 2005;Guérin et al., 2008;Barros et al., 2011;Teodoru et al., 2011). As the amount of labile OM originating from the flooded soils and biomass decreases with time due to the progressive mineralisation of the carbon stock, emissions decrease progressively with reservoirs ageing (Abril et al., 2005;Barros et al., 2011). CO_2 emissions are higher in tropical reservoirs than in temperate and boreal ones, a latitudinal difference attributed to the enhancement of OM degradation with temperature (Barros et al., 2011;Marotta et al., 2014;Yvon-Durocher et al., 2014). Emissions occur through diffusion at the air-water interface of the reservoir and from rivers downstream of dams (Abril et al., 2005;Guérin et al., 2006;Kemenes et al., 2011). At the surface of reservoirs, it is well known that emissions vary significantly spatially and temporally. Spatial variations can be higher than temporal variations (Roland et al., 2010;Teodoru et al., 2011;Zhao et al., 2013;Pacheco et al., 2015). Thus, the integration of both temporal and spatial variations is mandatory for the determination of accurate emission factors.

In some reservoirs with large water level variations, large surface areas of soils known as drawdown zones are periodically exposed to the atmosphere (for example, Three- Gorges and Nam Theun 2 reservoirs). Recently, the importance of the drawdown emissions was pointed out as a significant source of CH_4 in the Three Gorges Dam in China (Chen et al., 2009;Chen et al., 2011;Yang et al., 2012) and a very minor source at Nam Theun 2 Reservoir (NT2R) (Serça et al., 2016). CO_2 emission from the drawdown area was only measured in agricultural plots of the drawdown area of the Three Gorges Dam (Li et al., 2016). However, the hypothesis of significant CO_2 emissions from those soils seasonally flooded and exposed to air was never tested in unmanaged drawdown area representative of tropical reservoirs with large water level variations. In the present study, we measured CO_2, organic and inorganic carbon concentrations and physico-chemical parameters at 9 stations in the NT2R and 16 stations downstream of the dam and the powerhouse. This weekly to fortnightly sampling was conducted in order to estimate emissions from the reservoir surface and downstream

Mis en forme : Non Surlignage
Mis en forme : Non Surlignage
Mis en forme : Non Surlignage
Code de champ modifié
Code de champ modifié

emissions during 4.5 years of monitoring after impoundment. We also measured CO_2 emissions from the large drawdown area of the NT2R that represented seasonally up to 65% of the maximum reservoir area during the study. The spatial, seasonal and interannual variation of emissions by all the above-listed pathways and their contribution to total gross CO_2 emissions will be discussed.

2 Material and Methods

2.1 Study site

The NT2R is located in Lao People's Democratic Republic (Lao PDR), it was impounded in April 2008 and was commissioned in April 2010. It floods 489 km^2 of very diverse types of ecosystems including forest, agricultural soils and wetlands (Descloux et al., 2011). Geological formations responsible for the soil development in the NT2R area are mainly composed by more or less consolidated sedimentary rocks (Lovatt Smith et al., 1996;Smith and Stokes, 1997). The parental rocks belong to the Khorat group and Phon Hong group formations (Cretaceous) with two main lithologies: (1) late cretaceous Maha Sarakham formation (i.e., evaporites and mudstones) and (2) aptian Khot Kruat formation (i.e., mainly fluvial formation of red siltstones and sandstones)

The NT2R, described in detail in Descloux et al. (2016);Deshmukh et al. (2016);Guérin et al. (2016) is under the influence of a monsoon subtropical climate with three main seasons: the cold dry season (CD, from mid-Oct. to mid-Feb.), the warm dry season (WD, from mid-Feb. to mid-June) and the warm wet season (WW, from mid-June to mid-Oct.). Owing to the large seasonal variations of the river discharges in the region, the reservoir area ranged seasonally between 489 in the WW season to 170 km^2 in the WD season during the course of the study. On the opposite, the surface of the drawdown area reached its maximum (320 km^2) when the water level was the lowest. During the monitoring, the wettest years were 2011 and 2013 with an average water discharge in the reservoir of ~270 m^3 s^{-1} whereas the driest year was 2012 with a discharge 230 m^3 s^{-1}. In 2011, in this single year the reservoir had the largest water level variations with the largest surface area of the monitoring in the wet season (491 km^2) and the smallest of the monitoring in the WD season (168 km^2). The NT2R is a trans-basin reservoir with two downstream sections: one below the powerhouse and one below the Nakai Dam (Figure 1). Except during the occasional use of the spillways, only 2m^3 s^{-1} of water are discharged downstream of the Nakai Dam in the Nam Theun River and around 240 m^3 s^{-1} are

Supprimé: 's

Supprimé: s

Supprimé: decreased

Supprimé: down to 170

Supprimé: 2011

Supprimé: 2

Supprimé: 2

133 released to the powerhouse, the regulating pond and finally the artificial downstream channel
134 before water reaches the Xe Bangfai River (Figure 1).

135 ## 2.2 Sampling strategy

136 The CO_2 and O_2 concentrations in water and the water temperature were determined in
137 surface waters of six pristine rivers and three rivers under the influence of the reservoir (10
138 stations) and in the artificial channel (5 stations) whereas it was done along vertical profiles in
139 the reservoir (9 stations) and the regulation pond (1 station) (Figure 1). At all sites located
140 downstream of the powerhouse, sampling was done weekly (from March 2010 to December
141 2013) whereas it was done fortnightly in incoming pristine rivers and in the reservoir (from
142 May 2009 to December 2013). The stations RES1-RES3 flooded dense forest, the stations
143 RES4-RES6 flooded degraded forest, the station RES7 flood swamps and the station RES8
144 flooded a rice field area (Descloux et al., 2011;Guérin et al., 2016). The station RES9 is
145 located at the water intake, an area of continuous vertical mixing of the water column, where
146 CH_4 emissions are enhanced (Guérin et al., 2016). Degassing of CO_2 was calculated below
147 the Nakai Dam, just below the turbines at TRC1, below the regulating dam (RD on Figure 1)
148 and at the aeration weir (AW on Figure 1). Bubbling of CO_2 was determined during five field
149 campaigns covering different seasons and sites in 2009, 2010 and 2011, and during a weekly
150 monitoring from March 2012 to August 2013 at seven stations. In the drawdown area, soil
151 description was conducted in June 2010 at six sites and CO_2 emissions were repeatedly
152 measured at 21 plots over those sites in June 2010, 2011 and 2013.

153 ## 2.3 In situ measurements and water analysis

154 Vertical profiles of O_2, pH and temperature were measured in situ at all sampling stations
155 with a multi-parameter probe Quanta® (Hydrolab, Austin, Texas) since January 2009. In the
156 reservoir, the vertical resolution was 0.5 m down to 5 m and and 1 m deeper. Surface and
157 deep-water samples for CO_2, dissolved organic carbon (DOC), particulate organic carbon
158 (POC) and dissolved inorganic carbon (DIC) concentrations were taken with a surface water
159 sampler (Abril et al., 2007) and a UWITEC™ sampling bottle, respectively. Water samples
160 for CO_2 determination were stored in serum glass vials, capped with butyl stoppers, sealed
161 with aluminium crimps and preserved (Guérin and Abril, 2007). CO_2 concentrations were
162 determined by the headspace technique and using the solubility coefficient of Weiss (1974) as
163 in Guérin et al. (2006). The CO_2 partial pressure in headspace was determined by gas

chromatography (GC) (SRI 8610C gas chromatograph, Torrance, CA, USA) equipped with a flame ionization detector and a methanizer (Chanudet et al., 2011). Commercial gas standards (400, 1000 and 3000 ppmv, Air Liquid "crystal" standards) were injected after every 10 samples for calibration. Detection limit was < 1 ppmv in headspace and duplicate injection of samples showed reproducibility better than 5%. For TIC, DOC and POC, analyses were performed with a Shimadzu TOC-V_{CSH} analyser. Filtered (0.45 µm, Nylon) and unfiltered samples were analysed for TIC and TOC. POC was calculated by the difference between TOC and DOC concentrations in unfiltered and filtered samples. The detection limit was 8 µmol L^{-1} and uncertainty was 2.0 µmol L^{-1} on TOC and DOC and 2.8 µmol L^{-1} on POC.

2.4 Organic and inorganic carbon inputs from the watershed to the reservoir

Carbon inputs were calculated on a monthly basis using monthly average of the river discharge of the four main tributaries of the NT2R. The Nam Theun River contributed 32% (27 m^3 s^{-1}) of the total discharge while Nam Xot (22 m^3 s^{-1}), Nam On (19 m^3 s^{-1}) and Nam Noy (25 m^3 s^{-1}) not monitored for biogeochemistry) contributed 23%, 22 and 24% respectively. For the Nam On River, the specific water discharge and POC, DOC, TIC and CO_2 from this river were used. For the other rivers, the specific water discharge of each river was used together with the average DOC, POC, TIC and CO_2 from Nam Theun, Nam Phao and Nam Xot Rivers all located in the Nam Theun watershed. Note that the Nam Phao reaches the Nam Theun River downstream of the Nakai Dam but we used this dataset together with the ones from other rivers to calculate the carbon inputs since the physico-chemical parameters and carbon concentrations are not different from other rivers in the watershed.

2.5 Diffusive fluxes and degassing

Diffusive fluxes at the air-water interface of the reservoir were calculated from the surface CO_2 concentrations, wind speed and rainfall rates using the gas transfer velocity formulations of Guérin et al. (2007) and MacIntyre et al. (2010) as already described for CH_4 fluxes from this reservoir (Deshmukh et al., 2014;Guérin et al., 2016). Based on physical modelling and in situ measurements (Chanudet et al., 2012), we determined that the station RES9 located at the water intake is representative of an area of about 3 km^2 (i.e. 0.6 % of the reservoir water surface at full reservoir water level), whatever the season (Guérin et al., 2016). This area was therefore used to extrapolate specific diffusive fluxes from this station. For other stations, diffusive fluxes are calculated with the daily meteorological parameters and reservoir water

Mis en forme : Exposant
Mis en forme : Exposant
Mis en forme : Exposant
Mis en forme : Exposant
Mis en forme : Exposant
Mis en forme : Exposant
Mis en forme : Exposant
Supprimé: 24
Supprimé: 23
Supprimé: 22
Mis en forme : Exposant
Supprimé: supply

surface area from the capacity curve. Degassing downstream of the powerhouse, the regulating dam and the aeration weir, all located along the artificial channel and downstream of the Nakai Dam (Figure 1), were computed using the CO_2 concentration upstream and downstream of these civil structures and the water discharge as in Deshmukh et al. (2016) for CH_4. The diffusion from the rivers and artificial channel below the powerhouse and the dam was calculated using a constant gas transfer velocity of 10 cm h^{-1} (Deshmukh et al., 2016).

2.6 CO_2 bubbling

Bubbling of CO_2 was determined with funnels (Deshmukh et al., 2014) during five field campaigns covering different seasons (between May 2009 and June 2011), and during a weekly monitoring from March 2012 to August 2013. During this monitoring, spatial variation was explored through measurements spread over six stations (Fig. 1) representative of the different types of flooded ecosystems (dense and medium forests, light and degraded forest and agricultural lands as determined by Descloux et al. (2011)), and with different depths (from 0.4 to 16 m) at each station. We stopped measuring bubbling at sites deeper than 16m after no ebullition was observed during the first three campaigns. Bubble samples were taken with a 50 mL-syringe and the syringe was immediately connected to a N_2-preflushed 10-mL serum vial, leading to a dilution factor of 5/6 (Guérin et al., 2007). Gas samples were analysed with the GC described above.

2.7 Soil descriptions and CO_2 fluxes from the drawdown area

Since the drawdown area of the NT2R could represent up to 65% of the surface area of the reservoir at the end of the WD season, emissions from this major area under the influence of flooding were evaluated. Soil types were determined together with CO_2 emissions. Soil description was carried out in June 2010 at 6 sites and soils from the station RES4S plot were characterized in detail in June 2013 (Figure 1, Table 1). Four sites were selected in the Nam Theun River riparian's area (NMR, RES2S, RES4S, RES8S'), one site in the flooded primary forest (RES3S) and one site in the flooded agricultural area (RES8S). Soil study was conducted through soil catenae of 2 to 4 soils profiles from the pristine soils on top ("upland" samples) to the shoreline of the reservoir ("shoreline" samples). One or two other soils profiles were performed in between ("interm.up" and "interm.down" samples, with interm standing for intermediate). Soil sampling was performed with an Edelman soil corer down to a depth of 1m, but only 0-20cm depth samples were considered in this study. Information on

Supprimé: s

Supprimé: s

horizon depth, soil texture and structure (e.g., compactness, porosity), color (Munssel chart for soil color), soil fauna activity and pedological features (e.g., redoximorphic features, concretions) were provided through soil description in the field. Samples for C, N, and pH were selected following the horizons apparition for each soil profile. They were manually decompacted and stored in plastic bags. Back in the laboratory, soil samples were dried out at room temperature under a laminar flow hood, sieved at 2 mm and properly split in two representative subsamples. One of the subsamples was crushed with an agate mortar before chemical analysis. The non-crushed subsample was dedicated to soil pH and granulometric measurements. C and N analysis where performed with a Elementar Vario EL III C/N/S analyser and soil pH measurements were performed in ultrapure water (18.2 MΩ) following ISO 11464 standard procedure.

At the 6 sites, fluxes were measured along the soil moisture gradient between the shoreline and the zone not impacted by the reservoir water level fluctuation. Three to four sites with contrasting moisture content were selected at each site. At those six sites, fluxes were measured at 21 plots in total and 40 CO_2 fluxes were gathered, mostly in duplicates (from 1 to 4 replicates) (Table 2). CO_2 emissions were measured during 3 field campaigns in 2010, 2011 and 2013 using stainless steel chamber (volume 12 L, 0.08 m^2) described in Serça et al. (1994) and Serça et al. (2016). At each site, two chambers were deployed in parallel and the collars were installed at least 1 hour prior to measurement. Air samples were taken and stored with the same methodology as for bubbling samples every 15 minutes in each chamber before subsequent GC analysis. It has to be noted that soil studies and measurement of fluxes were restricted for safety reason due to the high density of unexploded ordnances (UXO) from the sixties and seventies in that area.

3 Results

3.1 Temperature, oxygen, pH, organic and inorganic carbon in the Nam Theun watershed and carbon inputs to the reservoir

In the rivers of the Nam Theun watershed, the water temperature was 24.5±0.2°C ranging from 13.5 to 32.0°C and pH was 6.83±0.03 (4.75-8.95, n=405). The Nam On River was, on average, less oxygenated (77±2%) than the others. It is characterized by the highest DOC concentrations (222±11 µmol L^{-1}, n=93), and amongst the highest CO_2 concentrations (59±6 µmol L^{-1}, n=107) and the lowest TIC concentration (237±11µmol L^{-1}, n=107) (Figure 2). The

Nam Phao and the Nam Theun Rivers are not significantly different in terms of POC, DOC, TIC and CO_2 concentrations (Figure 2). During the monitoring, the average DOC in the Nam Phao was 87±4 µmol L^{-1} (n=82) and 108±4 µmol L^{-1} (n=97) in the Nam Theun, that is more than two times lower than in the Nam On. TIC was 40% higher in the Nam Theun and Nam Phao Rivers than in the Nam On (Nam Phao: 380±12 µmol L^{-1}, n=82; Nam Theun: 379±15 µmol L^{-1}, n=97) (Figure 2). CO_2 in the Nam Theun River (54±5 µmol L^{-1}, n=105) and in the Nam Phao (46±5 µmol L^{-1}, n=86) contributed around 15% of TIC whereas it was almost 25% in the Nam On. The Nam Xot River had amongst the lowest DOC (90±3 µmol L^{-1}, n=93), TIC (272±12 µmol L^{-1}, n=94) and CO_2 (45±3 µmol L^{-1}, n=110) concentrations (Figure 2). Comparing results from all rivers, we could not find any significant differences in POC concentration. In all rivers during this monitoring, the average POC was 28±2 µmol L^{-1} (n=200) and contributed less than 20% of the total organic carbon (DOC+POC) in this watershed (Figure 2). We could not identify any clear seasonal pattern for POC, DOC TIC and CO_2 concentrations in the four rivers of the Nam Theun watershed (Figure 2).

As reported in Descloux et al. (2016), the average total water discharge in the reservoir is 238 m^3 s^{-1} ranging from 6 m^3 s^{-1} during the WD seasons to 2061 m^3 s^{-1} during the WW seasons. Carbon input to the reservoir as DOC, POC and TIC ranged from 32.2±1.3 GgC yr^{-1} in 2010 to 46.2±1.5 GgC yr^{-1} in the wet year 2011 (Figure 3). During the monitoring, TIC represented 60 to 70% of the carbon inputs to the reservoir (Figure 3).

3.2 Vertical profiles of temperature, O_2, pH, CO_2 and organic carbon in the reservoir water column

At the stations RES1-RES8, the typical vertical distributions of temperature, O_2, DOC, POC and CO_2 for the three seasons at various sampling stations are shown in Figure 4. As already described in detail in Guérin et al. (2016), during the four years of monitoring, the reservoir water column was thermally stratified during the warm seasons with thermocline at 4.5±2.6 and 5.8±4.8 m depths during the WD and WW seasons, respectively. As a consequence of thermal stratification, the warm epilimnic waters are well oxygenated (>80% saturation) whereas the hypolimnion is anoxic (Figure 4). Occasionally, sporadic and local destratification occurred during high water inflow in the WW season. During the CD season, temperature and O_2 decreased gradually with depth or O_2 concentration was constant from the surface to the bottom of the water column (Figure 4). After the power plant commissioning,

Supprimé: s

the water column located near the Turbine Intake (RES9) got totally mixed as revealed by the homogeneous temperature and O_2 profiles from the surface to the bottom (Figure 4). pH always decreased from the surface to the bottom with, on average during the monitoring, surface pH = 6.66±0.02 (5.21-8.76, n=1316) and hypolimnic pH = 6.15±0.01 (4.88-8.00, n=1488).

Over the monitoring period at the stations RES1-RES8, the average CO_2 concentration in the water column was 389±9 µmol L^{-1} and ranged from 0.3 to 4770 µmol L^{-1} (n=3698). It decreased from 544±24 µmol L^{-1} in 2010 to 154±9 µmol L^{-1} in 2013. During the WD and WW seasons, CO_2 concentrations increased with water depth and often showed a maximum gradient at or just below the thermocline (Figure 4). For the years 2010 to 2013, the average CO_2 concentrations in the water column during the WD and WW seasons were always 50% higher than in the CD season (Figure 4). DOC concentrations averaged 181±1 µmol L^{-1} and ranged from 12.5 to 569 µmol L^{-1} (n=3068). For the years 2010, 2011 and 2012 we observed a significant decrease of DOC in the water column from year to year with average DOC concentrations 208±3 µmol L^{-1} in 2010, 190±3 µmol L^{-1} in 2011 and 177±2 µmol L^{-1} in 2012. In 2013, the DOC was not significantly lower than in 2012 (175±2 µmol L^{-1}). From 2010 to 2013, DOC concentrations were about 25% higher in the WD and WW seasons than in the CD season. Whatever the year, the average epilimnic DOC concentration was 30% higher than in hypolimnic water. POC concentration was 63±2 µmol L^{-1} (n = 2488). POC in hypolimnic waters (92±3 µmol L^{-1}) was almost twice higher than in the epilimnion (45±2 µmol L^{-1}) ($p < 0.0001$, t-test). The POC in the epilimnion decreased significantly from 41±4 µmol L^{-1} in 2010 to 23±2 µmol L^{-1} in 2013 in the epilimnion ($p < 0.0001$). POC in hypolimnic waters did not show any consistent trend with yearly average values being 87±6 µmol L^{-1} in 2010, 67±6 µmol L^{-1} in 2011, 104±7 µmol L^{-1} in the wet year 2012 and 83±5 µmol L^{-1} in 2013. No clear seasonal variation was observed.

At the station RES9 where the presence of the water intake enhances vertical mixing of the water column leading to the transport of bottom water to the surface, the water column is not thermally stratified and always oxygenated from the surface to the bottom after the reservoir was commissioned in April 2010 (Guérin et al., 2016) (Figure 4). Since commissioning, O_2 saturation was 60±2 % over the water column. The water column was significantly more oxygenated during the overturn in the CD (74±3%) than in the WW and WD season (56±2%)

($p < 0.0001$, t-test) and significantly more oxygenated ($p < 0.0001$) in the wet year 2011 (70±3% on average) than in 2010 and 2012 (56±3% on average). In 2013, which was an average hydrological year, the water column was well oxygenated with 71±1% suggesting of improvement of the water quality. CO_2 concentrations were almost constant from the surface to the bottom and averaged 216±13 µmol L^{-1} over the whole monitoring period (n = 512) (Fig. 4). CO_2 concentration in the water column decreased from 311±32 µmol L^{-1} in 2010 down to 28±2 µmol L^{-1} in 2013. Concentrations in the WW and WD seasons were similar 204±14 µmol L^{-1} and more than two times higher than during the CD season (105±6 µmol L^{-1}). POC concentration was 25±1 µmol L^{-1} (n=431) and DOC was 157±2 µmol L^{-1} (n=642) over the whole water column and both follow the same seasonal variations and temporal variations as described for the other stations.

Supprimé: the

3.3 Reservoir surface CO_2 concentration and diffusive fluxes

The reservoir surface CO_2 concentrations (n=1067) ranged from 0.3 to 970 µmol L^{-1} (Figure 5a,b) and diffusive fluxes ranged from -40.4 up to 2694.9 mmol m^{-2} d^{-1} (Figure 5c,d). Most of the dataset (85% of all measurements) showed CO_2 supersaturation with respect to the atmosphere. In 2009 (from May to December), surface concentrations and diffusive fluxes from all nine sampling stations located in the reservoir were statistically similar ($p > 0.05$, ANOVA test). The average surface concentration was 68.2±47.9 µmol L^{-1} and the diffusive flux was 101.6±137.7 mmol m^{-2} d^{-1}.

From 2010 to 2013 at the stations RES1 to RES8, the yearly average surface CO_2 concentrations decreased significantly from 62.7±3.6 to 32.7±3.2 µmol L^{-1} while diffusive fluxes decreased from 89.8±10 to 13.7±4.7 mmol m^{-2} d^{-1} without any significant spatial variations ($p > 0.05$, ANOVA test). Over the 2010-2012 period, the highest concentration and fluxes were always observed in the WD season (70±3 µmol L^{-1} and 90±9 mmol m^{-2} d^{-1}), they decreased down to 51±3 µmol L^{-1} and 65±8 mmol m^{-2} d^{-1} in the WW and reached their minima in the CD season (45±3 µmol L^{-1} and 22±2 mmol m^{-2} d^{-1}) (Figure 5 a,c). In 2013, the reservoir was a net CO_2 sink from March to August (-11±2 mmol m^{-2} d^{-1}, n=96) and emissions in the CD season was 66±9 mmol m^{-2} d^{-1} (n=41) that is three times higher than usually observed for that season.

Mis en forme : Indice

At the water intake (RES9) after the commissioning, surface concentrations and diffusive fluxes were statistically different from the other stations and were significantly higher as

already observed for CH_4 (Guérin et al., 2016). The average surface CO_2 concentrations at RES9 were 287±350 and 184±234 µmol L^{-1} for the year 2010 and 2011, respectively that is three-five fold higher than the average at the other stations (Figure 5b). In 2012, surface CO_2 concentrations at RES9 dropped down to 65±23 µmol L^{-1}, still almost twice the concentration at the other stations. In 2013, surface concentration at RES9 was not statistically different than at the other station in the reservoir (33±4 µmol L^{-1} in 2013). On an annual basis, the diffusive fluxes at RES9 decreased from an average of 745±195 to 18±9 mmol m^{-2} d^{-1} between 2010 and 2013 (Figure 5d). The same seasonality as described before was observed at RES9 with an exacerbated effect at the transition between the WD and WW seasons since diffusive fluxes were then up to 17-fold higher than the average fluxes at the other stations for that same period (Figure 5c,d).

Monthly emissions by diffusive fluxes varied by two orders of magnitude between 2009 and 2012. Superimposed on the general decrease of emissions with time, we observed very significant seasonal variations with emissions peaking during the transition between the WD and WW seasons, even though the reservoir water surface was at its minimum (Figure 5e). The annual diffusive CO_2 emission from the reservoir was 730.0±46.2 Gg(CO_2) $year^{-1}$ in 2009 and dropped down by a factor of six in 2013 (118±11.5 Gg(CO_2) $year^{-1}$) (Figure 5f).

Supprimé: to

3.4 O_2, pH, organic carbon and CO_2 downstream of the reservoir

After the commissioning, immediately downstream of the power station (station TRC1), the average O_2 concentration was 174±58 µmol L^{-1}, that is, 67±20% saturation (n=189) and pH was 6.55±0.04 (n=234). Further downstream, the O_2 concentration always increased and the O_2 saturation downstream of station DCH4 located 30 km from the turbines was always around 100% saturation in the artificial downstream channel (average 100.4%, n=146). Just below the regulating dam, in the Nam Kathang River (NKT3), the average O_2 concentration was 237 µmol L^{-1}, that is, 93% saturation (n=120). There was no marked interannual change in the O_2 concentration. At DCH4, pH increased to 7.17±0.04 (n=186).

On average at all the stations in between TRC1 and DCH4, DOC concentration was 159±2 µmol L^{-1} (n=1366) over all stations for all years between 2009 and 2013. DOC decreased from 187±2 µmol L^{-1} in 2010 (n=272) to 157±2 µmol L^{-1} in 2013 (n=303). Average POC was 25±1 µmol L^{-1} (n=818) for all years between 2009 and 2013, and followed interannual

variations already observed for the reservoir, i.e. higher POC concentration in the WW season of 2012.

CO_2 concentration below the Powerhouse (TRC1), which receives water from the station RES9 in the reservoir after the water transiting through the turbines, varied by almost three orders of magnitude; ranging from 1.4 to 856 µmol L^{-1} with an average of 153±14 µmol L^{-1} (n =199). The CO_2 concentrations varied seasonally with maximum concentrations at the end of the WD season, and minimum at the end of the CD season. Below the powerhouse, along the longitudinal transects from TRC1 to DCH4, surface CO_2 concentration decreased by a factor of three within a distance of 30 km during the WD and WW seasons (from 267±34 to 90±10 µmol L^{-1} and from 235±28 to 70±8 µmol L^{-1} respectively for WD and WW). In the CD season when CO_2 concentrations were lower, the decrease in concentration with distance from the dam was only by a factor of two (from 49±8 to 30±4 µmol L^{-1}). Between 2010 and 2013 for all stations in the downstream channel (TRC1 to DCH4), annual average CO_2 concentrations decreased by a factor of 7 from 182±9 µmol L^{-1} to 24±2 µmol L^{-1}. On average, CO_2 concentration reached down to 56±5 µmol L^{-1} at DCH4 which is in the same order of magnitude as the concentrations found in the pristine Xe Bangfai River (XBF1, 60±2 µmol L^{-1}, n=64), Nam Kathang Noy River (NKT1, 35±3 µmol L^{-1}, n=47) and Nam Kathang Gnai River (NKT2, 82±10 µmol L^{-1}, n=70).

Immediately downstream of the Nakai Dam (NTH3) after the commissioning, the average O_2 concentration was 224 µmol L^{-1}, that is 87% saturation (n=73), and the concentration increased further downstream. pH was 6.84±0.06 (n=166). Average DOC concentration was 166±2 µmol L^{-1} (n=653) and decreased from 197±4 µmol L^{-1} in 2010 (n=147) to 162±3 µmol L^{-1} (n=127) in 2013. The average POC concentration was 50±5 µmol L^{-1} (n=7) and CO_2 concentration was 67±9 µmol L^{-1} (n=77). The CO_2 concentration decreased by a factor of two (40±5 µmol L^{-1}, n=54) within the next 10 km below the dam (down to NTH4, Figure 1) where pH was 7.19±0.06 (n=97). At NTH4, the observed concentrations were in the same order of magnitude than the concentrations in the pristine rivers in the same watershed (53±6 µmol L^{-1} at NPH1 in the Nam Phao River, n=59).

3.5 CO_2 emissions downstream of the reservoir

After the commissioning, the annual average diffusive fluxes downstream of the powerhouse decreased from 482±603 mmol m^{-2} d^{-1} in the year 2010 (-32–33762 mmol m^{-2} d^{-1}) to 32±8 mmol m^{-2} d^{-1} (-39–216 mmol m^{-2} d^{-1}) in 2013 (not show). They followed the same seasonal dynamics as the CO_2 concentrations and they decrease with the distance from the powerhouse. Total emissions by diffusion from the downstream channel decreased from 14±12 Gg(CO_2) $year^{-1}$ in 2010 to 1.3±0.5 Gg(CO_2) $year^{-1}$ in 2013 (Figure 6a). Degassing in the whole downstream channel (including degassing below the turbines, the regulating pond and the aeration weir) reached up to 28.5 Gg(CO_2) $month^{-1}$ just after the commissioning of the reservoir when the water was released for the first time (Figure 6a). During the monitoring, 60-90% of the annual degassing occurred within 3-4 months of transition between the WD and WW seasons corresponding to the seasons when the hypolimnic waters were the most enriched in CO_2 (Figure 6a). Total degassing decreased from 80±36 Gg(CO_2) $year^{-1}$ in 2010 to 8±4 Gg(CO_2) $year^{-1}$ in 2013 (Figure 6b).

Disregarding periods of spillway releases from April to June 2009 for water level regulation and in September-October 2011 during the flood, degassing downstream of the Nakai Dam (up to 0.48 Gg(CO_2) $month^{-1}$) is usually 10 times lower than degassing in the downstream channel because of (1) the low continuous water discharge at the Nakai Dam (2 m^3 s^{-1}) and (2) the withdrawal of the water from the reservoir epilimnion (Deshmukh et al., 2016) (Figure 6a). However, during the use of spillways for water level regulation in the reservoir, degassing reached up to 26 Gg(CO_2) $month^{-1}$ in 2009 before the commissioning and 4 to 10 Gg(CO_2) $month^{-1}$ during the occasional uses in October 2010 and September 2011 (Figure 6a). As determined from the longitudinal profiles of CO_2 concentrations downstream of the dam, diffusive emissions from the Nam Theun River that are actually attributable to the NT2R occurred within the first 10 km below the dam as it was also the case for CH_4 (Deshmukh et al., 2016). The annual average diffusive CO_2 fluxes were 126±137 and 288±346 mmol m^{-2} d^{-1} in 2010 and 2011 respectively. The annual average diffusive CO_2 flux was one order of magnitude lower in 2013 (24±68 mmol m^{-2} d^{-1}) (not show). The total emissions by diffusion and degassing resulting from these fluxes ranged between 5.5±0.1 Gg(CO_2) $year^{-1}$ in 2010 and 0.14±0.06 Gg(CO_2) $year^{-1}$ in 2013 (Figure 6b).

Supprimé: -

Supprimé: -

On a yearly basis, emissions downstream of NT2R decreased from 99.7±25.3 to 15.0±6.5 Gg(CO_2) y^{-1} between 2010 and 2013 (Figure 6b). Before the reservoir commissioning in 2009, emissions were dominated by degassing due to spillway releases. After the commissioning, emissions were dominated by degassing in the downstream channel which contributed 80-90% of total downstream emissions.

3.6 CO_2 bubbling

The CO_2 content in the sampled bubbles was 0.29±0.37% (n=2334). On average, the CO_2 bubbling was 0.16 ± 0.24 mmol m^{-2} d^{-1} (0-2.8 mmol m^{-2} d^{-1}) for depth shallower than 16m. Considering the water surface variations, the monthly ebullitive CO_2 emissions ranged from 0.04±0.06 to 0.11±0.16 Gg(CO_2) $month^{-1}$. CO_2 bubbling was constant around 1.1±2.2 Gg(CO_2) y^{-1} throughout the monitoring.

3.7 CO_2 emissions from the drawdown area

Four types of pristine soils were identified in the six different studied catenae. Acrisols were the most represented soils and were found at three sites (RES4S, RES8S and RES8'S) (Table 1). In the area with dense forest, soils were characterized as plinthosol (RES3S) and plinthic ferralsol (RES2S) and the pedological cover at MNR site belong to planosol type soil (Table 1). At all sites, from upland pristine soils to the shoreline, stagnic properties were more and more pronounced. Average organic carbon content (%C), nitrogen (%N) and C:N ratio were 1.84±0.10%, 0.14±0.01% and 12.83±0.30, in surface horizons, respectively. For those three parameters, no statistical differences were obtained according to soil type, topography or measurement site. Diffusive CO_2 fluxes ranged between 34±7 and 699±59 mmol m^{-2} d^{-1} (Table 2). The fluxes were not significantly correlated with the surface moisture (17.5 to 51.2%) and temperature (18.1 to 34.2°C) (Table 2). The fluxes neither varied significantly with soil types, topography, measurement sites, nitrogen content or C:N ratio ($p > 0.05$, ANOVA test). However, average fluxes at each site were significantly correlated with the average C content (p=0.0452). Since we did not observe significant spatial variations related to topography, humidity or temperature that could have been considered for refine spatial and temporal extrapolation, we further consider the average of all fluxes that is 279±27 mmol m^{-2} d^{-1} throughout the years.

Supprimé: 6d

Supprimé: and no bubbles was ever observed for depth higher than 16 m

Supprimé: ranging from

Supprimé: ranging from

Supprimé:

Supprimé: Without

Mis en forme : Non Exposant/ Indice

After the commissioning of the reservoir, emissions varied by three orders of magnitude. Since a constant CO_2 emission is accounted for, the seasonal pattern of CO_2 emission from the drawdown mimics the variation of the surface of that area (Figure 7). Monthly CO_2 emissions have reached up to 110.8±10.7 Gg(CO_2) month^{-1} by the end of the WD season when drawdown area reached its maximum whereas it decreased down to 0.6±0.1 Gg(CO_2) month^{-1} at the end of WW season when drawdown area reached its minimum (Figure 7). Around 80-90% of the annual emissions occurred within 4-6 months of transition period between the WD and WW seasons (Figure 7) when the drawdown area surface is at its maximum. The lowest emissions from the drawdown area occurred during the wet year 2011 (386±16 Gg(CO_2) year^{-1}) and the highest emissions during the dry year 2012 (572±20 Gg(CO_2) year^{-1}).On average from 2009 to 2013, emissions from the drawdown area was 431±42 Gg(CO_2) year^{-1}.

Supprimé: could

Supprimé: reaches

Supprimé: reaches

4 Discussion

4.1 CO_2 dynamic in the NT2R water column and downstream rivers

The dynamics of CO_2 in the NT2R is highly dependent on the hydrology and hydrodynamics of the reservoir as it has already been described for CH_4 (Guérin et al., 2016). During the warm seasons (WD and WW) when the water column is thermally stratified, the vertical profiles of CO_2 concentration in the water column are similar to profiles obtained in other tropical or subtropical reservoirs (Abril et al., 2005;Guérin et al., 2006;Kemenes et al., 2011;Chanudet et al., 2011) but also boreal reservoirs (Demarty et al., 2011). The high concentrations measured in the hypolimnion suggest that the main source of CO_2 is located at the bottom and very likely in the flooded soils, vegetation and sediments whereas the decrease of CO_2 toward the surface suggest both consumption by primary production and/or loss to the atmosphere (Galy-Lacaux et al., 1997b;St Louis et al., 2000;Abril et al., 2005;Guérin et al., 2008;De Junet et al., 2009;Teodoru et al., 2011;Barros et al., 2011;Chanudet et al., 2011). In the CD season, after the reservoir overturn, the average CO_2 concentration in the reservoir water column decreases sharply (by 50% on average) and CO_2 concentration increases regularly from the surface to the bottom of the water column. However, no CO_2 burst was observed at the beginning of the CD season evidencing that reservoir overturn has only a moderate impact on CO_2 emissions. This assumption is reinforced by the fact that during the same sampling, hot moments of CH_4 emissions that should have occurred at the same time were captured (Guérin et al., 2016). As observed in most tropical and subtropical reservoirs,

Supprimé: when the reservoir overturns. Therefore it is reasonable to assume that the

the higher concentrations were observed during the warm seasons due to long residence tie of water and warmer conditions enhancing CO_2 build-up (Abril et al., 2005;Kemenes et al., 2011;Chanudet et al., 2011) whereas the lowest were found after reservoir overturn when the water outgassed (Chanudet et al., 2011). A significant shift in the carbon biogeochemical cycling occurred in the reservoir in 2013 with the reservoir water surface becoming of CO_2 sink during the WD season and the beginning of the WW season (from March to August). Although no major change was observed in nutrient concentrations, the number of phytoplanktonic cell was 50% higher in 2013 than 2012 (Unpublished, M Cottet personal com.) indicating that primary production was significantly enhanced in 2013. Despite the fact that the reservoir was a sink for the six months when CO_2 emissions are usually the highest of the year, annual CO_2 emissions at the surface of the reservoir were only 50% lower in 2013 than in 2012. In 2013, CO_2 was mainly emitted in the CD after the period of high biological productivity suggesting that the degradation of autochthonous OM fuels CO_2 emissions.

The maximum concentration and the highest CO_2 stock in the water column highly depend on the age of the reservoir. In the NT2R, average CO_2 concentration was three times higher in 2010 than in 2013 and the maximum concentrations in 2010 was almost two times higher than in 2013 (4771 µmol L^{-1} in 2010 vs. 2649 µmol L^{-1} in 2013). Those high concentrations are slightly lower than the maximum concentration measured in the hypolimnion of the Petit Saut Reservoir less than a year after it was flooded (Galy-Lacaux et al., 1997a;Abril et al., 2005). Disregarding these high concentrations observed in the hypolimnion of the reservoir at the end of the WD season and beginning of the WW season in 2009 and 2010, the CO_2 concentration in the NT2R are in the same range as concentrations in other older reservoirs in the tropics or the subtropics (Abril et al., 2005;Guérin et al., 2006;Chanudet et al., 2011;Kemenes et al., 2011). This decrease during the first four years after impoundment is very consistent with the decrease of the CO_2 concentration with the reservoir age as already observed at the Petit Saut Reservoir (Abril et al., 2005), at the Eastmain I Reservoir (Teodoru et al., 2012) or over multi-sites study (Barros et al., 2011).

Disregarding the station RES9 located at the water intake, no significant spatial variation of CO_2 surface concentrations was found despite very significant differences of hypolimnic concentration between stations located upstream of the Nakai Dam (RES1, 2 and 3) and station located in areas close to the three main tributaries (RES6, 7 and 8). The average hypolimnic concentrations at the stations RES1-3 were two times higher than at the stations

Mis en forme : Indice

554 RES6-8. This difference is attributed to both (1) the difference in carbon density at the bottom
555 of the reservoir in those two contrasted areas in terms of submerged ecosystems (Descloux et
556 al., 2011) (see section 4.3) and (2) the difference in terms of water residence time between
557 those two zones (Guérin et al., 2016). Stations RES1-3 are located in areas with the longest
558 water residence time in the reservoir since the water mostly enters the reservoir in the RES6-8
559 area from the Nam Theun, Nam Noy and Nam On Rivers before being delivered to the water
560 intake (close to RES9) on the opposite side of NT2R which has a narrow and elongated shape
561 (Figure 1). Therefore, the water renewal in the RES6-9 area is high and CO_2 accumulates less
562 in the water column confirming the importance of the reservoir hydrology on the spatial
563 variability of dissolved gases in reservoirs (Pacheco et al., 2015;Guérin et al., 2016).

564 As found for CH_4, the main factor influencing the spatial variability of CO_2 in the water
565 column is the vertical mixing of the water column induced by the water intake located close to
566 RES9 (Deshmukh et al., 2016;Guérin et al., 2016). The design of the water intake enhances
567 horizontal water current velocities and vertical mixing which lead to the transport of bottom
568 waters to the surface. As a consequence, surface concentrations at RES9 were up to 30 times
569 higher than at other stations in 2010 and 2011 (Figure 5b). With the significant decrease of
570 concentrations in 2012 and 2013, the difference with other stations dropped to a factor of
571 four. These maximum surface concentrations at RES9 are up to 10 times higher than
572 concentrations found in other tropical reservoir in South America (Abril et al., 2005;Guérin et
573 al., 2006;Kemenes et al., 2011) and Lao PDR (Chanudet et al., 2011) showing that, as for
574 CH_4, CO_2 emissions can be enhanced upstream of water intake or dams.

575 Downstream of the reservoir in the Nam Theun River or the artificial channel, CO_2
576 concentrations follow the same seasonality as in the reservoir. Concentrations peak in June-
577 July at the transition between the WD and the WW season, and reach their minima in the CD
578 season. Downstream of the Nakai Dam, the concentrations are twice lower than downstream
579 of the powerhouse since mostly epilimnic water from the RES1 station is transferred
580 downstream of the dam. Within less than 10 km further downstream, concentrations are not
581 significantly different than in pristine rivers of the watershed. Downstream of the
582 powerhouse, CO_2 concentrations in 2010 were in the same order of magnitude as in 10-20
583 years-old reservoirs in South America flooding tropical forest (Abril et al., 2005;Guérin et al.,
584 2006;Kemenes et al., 2011) whereas four years after impoundment CO_2 concentrations were
585 two times lower than in 20-30 years-old reservoirs in Lao PDR (Chanudet et al., 2011). We

Supprimé: higher

hypothesize that the low CO_2 concentration downstream of the NT2R result from a significant degassing of the water at the water intake before the water is transferred downstream as observed for CH_4 (Deshmukh et al., 2016;Guérin et al., 2016).

4.2 Total CO_2 emissions from the Nam Theun 2 Reservoir

From 2009 to 2013, total CO_2 emissions from NT2R show the same seasonal pattern (Figure 8a). The lowest total emissions occur in the CD season while the highest emissions occur at the transition between the WD and the WW season when emissions by all individual pathways reach their maximum. From 2010 to 2013, emissions at the transition between the WD and the WW seasons (April-July) contributed 47 to 61% of total annual emissions suggesting that quantification of emissions based on two to four campaigns in a year might be subject to caution since seasonality of emissions significantly affects emission factors.

Supprimé: between

Supprimé: and

Supprimé: s

CO_2 bubbling follows the same seasonal variations, being triggered by water level and concomitant hydrostatic decrease as for CH_4 (Chanton et al., 1989;Engle and Melack, 2000;Smith et al., 2000;Boles et al., 2001;Deshmukh et al., 2014) but its contribution is negligible (<1%, Table 3). Low CO_2 emission by bubbling as also observed in temperate reservoirs (Bevelhimer et al., 2016) is attributed to the higher solubility of CO_2 in water than CH_4 which lead to the solubilisation of the majority of CO_2 as free CO_2 or as DIC.

The relative contribution of emissions downstream of the reservoir by degassing and diffusion from rivers and channels at NT2R are low as compared to most of the reservoirs that were studied (Abril et al., 2005;Guérin et al., 2006;Kemenes et al., 2011;Bevelhimer et al., 2016) but the contribution of this pathway is comparable to what was observed in boreal reservoirs (Roehm and Tremblay, 2006) or in monomictic reservoirs from Lao PDR (Chanudet et al., 2011). The downstream emissions contributed between 11% at the maximum in the wet 2011 year down to 3% at the minimum in 2013 (Table 3 and Figure 8a). As for CH_4 at NT2R (Deshmukh et al., 2016), the low downstream emissions are attributed to the significant degassing at the water intake (station RES9) before the water reach the turbines and to the flush of CO_2 due to the reservoir overturn in the CD season.

Emissions by diffusive fluxes at the surface of the reservoir increased by a factor of two by the end of the WD season (Figure 5a) compare to the CD season from 2009 to 2012. The average CO_2 emissions in 2009 and 2010 and in a lesser extend 2011 are in the same range as emissions from the Petit Saut Reservoir during the first five years after impoundment (Abril et

al., 2005) and in the upper range of average CO_2 diffusive fluxes measured in older tropical reservoirs (dos Santos et al., 2006;Kemenes et al., 2011;Yang et al., 2013) or in young boreal reservoirs (Teodoru et al., 2011;Tadonléké et al., 2012). In 2012 and 2013, emissions from NT2R by diffusive fluxes are still higher than most of the older Asian reservoirs (Wang et al., 2011;Chanudet et al., 2011;Zhao et al., 2013;Xiao et al., 2013;Panneer Selvam et al., 2014) and other Brazilian reservoirs flooding savannah (Roland et al., 2010;Pacheco et al., 2015). The low emissions in the CD season from the first 3.5 years might mostly result from lower heterotrophic activity due to the low temperature (down to 7°C in air in March 2011). The high emissions in the CD season of 2013 as compared to CD season in 2011 and 2012 likely to be originated from additional autochthonous OM. We hypothesise that the significantly higher CO_2 emissions in the WD season result from the increase of the water residence time that favour CO_2 accumulation in the water column (Abril et al., 2005) and the increase of temperature that enhance aerobic and anaerobic degradation of OM and the production of CO_2 (Sobek et al., 2005). Although the reservoir area during the WD season is the smallest of the year, emissions by diffusive fluxes are the highest (Figure 8a) highlighting the very significant increase of CO_2 emissions from May to July every year, disregarding the year 2013.

This first estimation of the CO_2 emission from the drawdown area to the total emission from a reservoir reveal that with a contribution ranging from 40 to more than 75%, it could be a major CO_2 pathway to the atmosphere. These results from the NT2R cannot be generalized to all reservoirs since its contribution is tightly link to the very high-water level variations and large surface area of the drawdown area (up to 320 km^2, Figure 7). However, areal fluxes from the drawdown area are on average 2.5 times higher than the diffusive fluxes from the reservoir water surface in 2009-2010 and six times higher than those fluxes in 2013 making the soils in the area of influence of the reservoir a hotspot for CO_2 emissions compare to the reservoir surface waters. The total emissions of reservoirs with contrasted hydrology characterized by marked wet and dry seasons and large water level variations of 30% of the total surface could have been significantly underestimated as it is the case for Petit Saut (~100 km^2), Samuel (~280 km^2), Balbina (~220 km^2) or Three Gorges Reservoir (~400 km^2) for instance (Guérin et al., 2006;Kemenes et al., 2011;Li et al., 2016). This pathway is expected to be more significant in flat bottom reservoirs than in valley type reservoirs in mountainous regions and cannot be generalized on just the drawdown area without taking into account hydrological water management and the local topography. At Petit Saut and NT2R at least, no

Supprimé: high water

vegetation regrowth occurs in the drawdown areas. Soils at NT2R exhibit very clear modification related to the flooding (stagnic features) confirming soil modification as also observed in Canada (Furey et al., 2004) Australia (Watts, 2000) and France (Félix-Faure et al., 2017). The ecosystems of the seasonally flooded area are therefore significantly modified and CO_2 emissions from the drawdown must be accounted for in total gross emissions from reservoirs. Although drawdown emissions cannot be neglected in terms of gross CO_2 exchange, the emissions resulting from the soil respiration are currently comparable to pristine emissions (Table 2) and the impact of these area in terms of net emissions requires further specific studies in these overlooked ecosystems (Prairie et al., 2017). So far, we cannot predict future evolution of CO_2 emissions in this area based on the available data. The consequence of the flooding on the respiration rate of these soils may lead to a decrease of emissions with time or a stabilization (see next section). Therefore, the net contribution of the drawdown zone to emissions from the reservoir remains unclear and specifically requires research on soil OM dynamics and would also require the inclusion of the vegetation dynamics when present.

This is the first comprehensive quantification of CO_2 emissions from a reservoir where all known CO_2 pathways to the atmosphere were taken into account at one of the best spatial and temporal resolution reported in the literature. We showed that downstream emissions and emissions around the water intake are not negligible (~10% overall) and that the overlooked drawdown area in CO_2 studies could be the main emission pathway of CO_2 to the atmosphere. Overall, this study highlights that global estimate of CO_2 emissions from reservoir are underestimated so far since relevant pathways like drawdown emissions in flat/shallow reservoirs with large water level variations and downstream emissions in thermally stratified reservoirs are missing in most site-specific studies used for extrapolations (Deemer et al., 2016;Barros et al., 2011).

Supprimé: ing

Supprimé: and CH_4

4.3 Source of organic matter fuelling the reservoir CO_2 emissions

In tropical reservoirs, the decrease of the CO_2 concentration in the water column and subsequent emissions with the age of the reservoir (Figure 8b) is supposed to result from the decrease of the aerobic and anaerobic mineralisation rate due to the exhaustion of labile OM from the pool of soil and vegetation that was flooded during impoundment (Abril et al., 2005;Guérin et al., 2008). In boreal reservoirs, the decrease of benthic CO_2 production is

688 sharp and after 3-5 years, most of the CO_2 production appears to be pelagic and is supposed
689 not to result from the flooded organic matter (Teodoru et al., 2011;Brothers et al., 2012). The
690 total CO_2 emissions were nine and three times higher than the carbon inputs from the
691 watershed to the NT2R in 2010 (32 GgC yr^{-1}) and 2013 (45 GgC yr^{-1}), respectively (Figure 3
692 and Table 3). It has to be noted that interannual variations of carbon inputs to the NT2R
693 (Figure 3) are not correlated with the regular decrease of total CO_2 emissions from year to
694 year (Figure 8b). It is therefore unlikely that most of CO_2 emissions result from the
695 mineralization of allochthonous OM but rather from the contribution of the flooded carbon
696 pool (soil and vegetation) which amount is decreasing with time. This is consistent with the
697 fact that at Petit Saut, even 10 years after flooding, the majority of the OM in the water
698 column has a terrestrial origin (De Junet et al., 2009). According to Abril et al. (2005) at Petit
699 Saut, total emissions (disregarding drawdown emissions which were not measured) were 9 to
700 6 times higher than carbon inputs from the watershed during the first 4 years for similar
701 carbon inputs which indicates a faster decrease of emissions in NT2R than at Petit Saut. This
702 sharp decrease of emissions at NT2R might be due to the fact that the flooded pool of OM and
703 therefore the amount of labile OM in NT2R was twice smaller than the amount of OM
704 flooded in the Petit Saut (Guérin et al., 2008;Descloux et al., 2011). We show here, as it was
705 done at Petit Saut (Guérin et al., 2008;Abril et al., 2005), that external sources of carbon are
706 not sufficient to fuel the CO_2 emissions from the NT2R and we attribute the decrease of
707 emissions with time to the exhaustion of the most labile fraction of the flooded pool of OM
708 which might be the main source of reactive carbon in the reservoir.

709 In the sub-tropical NT2R, CO_2 concentrations are always higher at the bottom than in the
710 epilimnic waters even during the CD season when the limited thermal stratification or its
711 absence do not favour hypolimnic CO_2 accumulation. The CD season is probably the most
712 favourable season to pelagic respiration as this process is enhanced by the re-oxygenation of
713 the water column (Bastviken et al., 2004). Since CO_2 concentration in the CD season is 50%
714 lower than in the warm seasons, we suggest that CO_2 is mostly produced in the sediment and
715 flooded soils and vegetation. Disregarding the station RES9 located at the water intake,
716 significant spatial variation of CO_2 hypolimnic concentrations were found between stations
717 located in the area of dense forest (RES1-3) versus stations located in areas close to the three
718 main tributaries (RES6-8). Stations RES1-3 which have the highest average bottom
719 concentrations are located in areas where the carbon density is 50% higher than the

agricultural ecosystems that were flooded in the area of the stations RES6-8 (Descloux et al., 2011).

In the absence of significant vegetation regrowth in the drawdown area during the study period, the main source of carbon fuelling emissions from the drawdown area are not clearly identified. Immediately after flooding, the most labile part of the soil OM and the decomposing vegetation must have been the main sources of C fuelling the emissions. On the long haul, the atmospheric carbon sink associated with the pristine vegetation dynamics has been lost but as a consequence, the loss of this vegetation which might reduce labile OM inputs. In addition, the water level variations erode the soil and OM is transferred to the reservoir and ultimately in the sediments or downstream (Félix-Faure et al., 2017). Those carbon losses should have resulted or should result in the future in a decrease of CO_2 emissions from the drawdown. The stability of emissions throughout our four-years surveys in the drawdown area suggests that new carbon source might have contributed to emissions. Development of micro-phytobenthos or microbial biofilms as often observed in estuaries on mudflats (de Brouwer and Stal, 2001) or along stream in logged riparian area (Sabater et al., 2000) could supply labile OM to the system and favour priming effect (Guenet et al., 2010). Through this effect, the inputs of labile OM stimulate the degradation/mineralization of recalcitrant/stabilized OM. This effect might be enhanced by the oxic/anoxic oscillation that would favour the mineralisation of different pool of OM than those that would have been degraded otherwise in stable conditions (Abril et al., 1999;Bastviken et al., 2004). Overall, we hypothesized that the oxic/anoxic variations and priming effect through the development of algae and bacteria might have contributed to the stability of CO_2 emission from these soils under the influence of the reservoir. So far we found no clear evidence of a significant carbon loss in the soils of the drawdown area by comparing surface SOM from pristine upland soils and from the shoreline (Table 1). A comprehensive study of carbon density down to the bedrock would be necessary since we found very clear evidence of inundation patterns down to 1 m (P. Oliva, unpublished). In addition to the full carbon stock, detailed OM characterisation might be needed for the identification of changes in the pool of soil OM.

The overall confirmation of the importance of the flooded pool of OM in the carbon cycling in a tropical reservoir highlights the differences in functioning with boreal reservoirs where the degradation of the flooded organic matter within a few year does not contribute significantly to emissions (Brothers et al., 2012). In addition to a strong temperature effect on

Supprimé: and

Supprimé: s

mineralisation of OM (Gudasz et al., 2010), the probable low lability and good capacity for preservation of peat-dominated OM might explain the different origin of OM fuelling emissions between those two distinct climatic areas.

5 Conclusions

We presented the first comprehensive estimation of CO_2 emissions from a subtropical reservoir starting less than a year after reservoir impoundment and lasting 4.5 years. This estimation includes all known pathways to the atmosphere: emissions from the reservoir surface, downstream emissions and emissions from the drawdown area.

More than 50% of total emissions occur within 3-4 months during the warmest period of the year at the transition between the dry and the wet season. Such a result suggests that quantification of emissions based on two to four campaigns in a year might significantly affect positively or negatively emissions factors and carbon budgets of ecosystems under study.

The smooth decrease of total emissions over the years coupled with the fact that the incoming flux of carbon from the watershed to the reservoir represents less than a third of the total emissions, are a strong indication that the flooded pool of organic matter is the main source of carbon fuelling emissions. The carbon density of flooded soil and biomass in reservoirs appears to be a key controlling factor of emissions and should be included for future estimation of greenhouse gas emissions from reservoirs.

Supprimé: with time

We found that gross CO_2 emissions from the drawdown area represented 40- 75% of the total emissions from the NT2R and they occur within a few months during low water level seasons. The soil organic matter from these areas undergoes anaerobic degradation and fuels the reservoir water column in CO_2 during the wet season. In the dry season, the soil loss CO_2 directly to the atmosphere while undergoing both aerobic and anaerobic mineralisation depending on the soil moisture content. We hypothesize that both (1) the potential development of bacteria and micro-phytobenthos at the surface of these soils and (2) the oxic/anoxic variations contribute to the mineralisation of stabilized SOM leading to a sustained high soil respiration even after the pristine vegetation decayed. This overlooked pathway in terms of gross emissions would require an in-depth evaluation for the soil OM and vegetation dynamics and long-term monitoring of emissions to evaluate the real contribution of this area in terms of net modification of gas exchange in the footprint of the reservoir.

Supprimé: up to

Acknowledgements

The authors thank everyone who contributed to the NT2 monitoring programme, especially the Nam Theun 2 Power Company (NTPC), Electricité de France (EDF) and CNRS-INSU (Submersoil project, EC2CO-BIOHEFECT) for providing financial, technical and logistic support. We are also grateful to the Aquatic Environment Laboratory of the Nam Theun 2 Power Company whose Shareholders are EDF, Lao Holding State Enterprise and Electricity Generating Public Company Limited of Thailand. CD benefited from a PhD grant by EDF.

795

796 **References**

797 Abril, G., Etcheber, H., Le Hir, P., Bassoullet, P., Boutier, B., and Frankignoulle, M.:
798 Oxic/anoxic oscillations and organic carbon mineralization in an estuarine maximum turbidity
799 zone (The Gironde, France), Limnology and Oceanography, 44, 1304-1315, 1999.

800 Abril, G., Guérin, F., Richard, S., Delmas, R., Galy-Lacaux, C., Gosse, P., Tremblay, A.,
801 Varfalvy, L., Dos Santos, M. A., and Matvienko, B.: Carbon dioxide and methane emissions
802 and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana), Global
803 Biogeochem. Cycles, 19, 10.1029/2005gb002457, 2005.

804 Abril, G., Commarieu, M.-V., and Guérin, F.: Enhanced methane oxidation in an estuarine
805 turbidity maximum, Limnol. Oceanogr., 52, 470-475, 2007.

806 Barros, N., Cole, J. J., Tranvik, L. J., Prairie, Y. T., Bastviken, D., Huszar, V. L. M., del
807 Giorgio, P., and Roland, F.: Carbon emission from hydroelectric reservoirs linked to reservoir
808 age and latitude, Nature Geosci, 4, 593-596, 2011.

809 Bastviken, D., Persson, L., Odham, G., and Tranvik, L.: Degradation of dissolved organic
810 matter in oxic and anoxic lake water, Limnology and Oceanography, 49, 109-116, 2004.

811 Bevelhimer, M., Stewart, A., Fortner, A., Phillips, J., and Mosher, J.: CO2 is Dominant
812 Greenhouse Gas Emitted from Six Hydropower Reservoirs in Southeastern United States
813 during Peak Summer Emissions, Water, 8, 15, 2016.

814 Boles, J. R., Clark, J. F., Leifer, I., and Washburn, L.: Temporal variation in natural methane
815 seep rate due to tides, Coal Oil Point area, California, Journal of Geophysical Research:
816 Oceans, 106, 27077-27086, 10.1029/2000JC000774, 2001.

817 Brothers, S. M., Prairie, Y. T., and del Giorgio, P. A.: Benthic and pelagic sources of carbon
818 dioxide in boreal lakes and a young reservoir (Eastmain-1) in eastern Canada, Global
819 Biogeochem. Cycles, 26, GB1002, 10.1029/2011gb004074, 2012.

820 Chanton, J. P., Martens, C. S., and Kelley, C. A.: Gas Transport from Methane-Saturated,
821 Tidal Freshwater and Wetland Sediments, Limnology and Oceanography, 34, 807-819, 1989.

822 Chanudet, V., Descloux, S., Harby, A., Sundt, H., Hansen, B. H., Brakstad, O., Serca, D., and
823 Guérin, F.: Gross CO2 and CH4 emissions from the Nam Ngum and Nam Leuk sub-tropical
824 reservoirs in Lao PDR, Sci. Total Environ., 409, 5382-5391, 10.1016/j.scitotenv.2011.09.018,
825 2011.

826 Chanudet, V., Fabre, V., and van der Kaaij, T.: Application of a three-dimensional
827 hydrodynamic model to the Nam Theun 2 Reservoir (Lao PDR), J. Great Lakes Res., 38, 260-
828 269, http://dx.doi.org/10.1016/j.jglr.2012.01.008, 2012.

829 Chen, H., Wu, Y., Yuan, X., Gao, Y., Wu, N., and Zhu, D.: Methane emissions from newly
830 created marshes in the drawdown area of the Three Gorges Reservoir, J. Geophys. Res., 114,
831 D18301, doi:10.1029/2009JD012410, 2009.

832 Chen, H., Yuan, X., Chen, Z., Wu, Y., Liu, X., Zhu, D., Wu, N., Zhu, Q. a., Peng, C., and Li,
833 W.: Methane emissions from the surface of the Three Gorges Reservoir, J. Geophys. Res.,
834 116, D21306, 10.1029/2011jd016244, 2011.

de Brouwer, J. F. C., and Stal, L. J.: Short-term dynamics in microphytobenthos distribution and associated extracellular carbohydrates in surface sediments of an intertidal mudflat, Marine Ecology Progress Series, 218, 33-44, 2001.

De Junet, A., Abril, G., Guérin, F., Billy, I., and De Wit, R.: A multi-tracers analysis of sources and transfers of particulate organic matter in a tropical reservoir (Petit Saut, French Guiana), River Research and Applications, 25, 253-271, 10.1002/rra.1152, 2009.

Deemer, B. R., Harrison, J. A., Li, S., Beaulieu, J. J., DelSontro, T., Barros, N., Bezerra-Neto, J. F., Powers, S. M., dos Santos, M. A., and Vonk, J. A.: Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis, BioScience, 10.1093/biosci/biw117, 2016.

Demarty, M., Bastien, J., and Tremblay, A.: Annual follow-up of gross diffusive carbon dioxide and methane emissions from a boreal reservoir and two nearby lakes in Qu√©bec, Canada, Biogeosciences, 8, 41-53, 10.5194/bg-8-41-2011, 2011.

Descloux, S., Chanudet, V., Poilvé, H., and Grégoire, A.: Co-assessment of biomass and soil organic carbon stocks in a future reservoir area located in Southeast Asia, Environ. Monit. Assess., 173, 723-741, 10.1007/s10661-010-1418-3, 2011.

Descloux, S., Guedant, P., Phommachanh, D., and Luthi, R.: Main features of the Nam Theun 2 hydroelectric project (Lao PDR) and the associated environmental monitoring programmes, Hydroécol. Appl., 19, 5-25, 2016.

Deshmukh, C., Serca, D., Delon, C., Tardif, R., Demarty, M., Jarnot, C., Meyerfeld, Y., Chanudet, V., Guedant, P., Rode, W., Descloux, S., and Guérin, F.: Physical controls on CH4 emissions from a newly flooded subtropical freshwater hydroelectric reservoir: Nam Theun 2, Biogeosciences, 11, 4251-4269, 10.5194/bg-11-4251-2014, 2014.

Deshmukh, C., Guérin, F., Labat, D., Pighini, S., Vongkhamsao, A., Guédant, P., Rode, W., Godon, A., Chanudet, V., Descloux, S., and Serça, D.: Low methane (CH4) emissions downstream of a monomictic subtropical hydroelectric reservoir (Nam Theun 2, Lao PDR), Biogeosciences, 13, 1919-1932, 10.5194/bg-13-1919-2016, 2016.

dos Santos, M. A., Rosa, L. P., Sikar, B., Sikar, E., and dos Santos, E. O.: Gross greenhouse gas fluxes from hydro-power reservoir compared to thermo-power plants, Energy Policy, 34, 481-488, 10.1016/j.enpol.2004.06.015, 2006.

Engle, D., and Melack, J. M.: Methane emissions from an Amazon floodplain lake: Enhanced release during episodic mixing and during falling water, Biogeochemistry, 51, 71-90, 2000.

Félix-Faure, J., Chanudet, V., Walter, C., Dorioz, J.-M., Baudoin, J.-M., Lissolo, T., Descloux, S., and Dambrine, E.: Evolution des sols ennoyés sous les retenues de barrage : Influence sur l'écologie des plans d'eau et la dynamique des gaz à effet de serre, Etude et Gestion des Sols, 24, 45-58, 2017.

Furey, P. C., Nordin, R. N., and Mazumder, A.: Water Level Drawdown Affects Physical and Biogeochemical Properties of Littoral Sediments of a Reservoir and a Natural Lake, Lake and Reservoir Management, 20, 280-295, 10.1080/07438140409354158, 2004.

Galy-Lacaux, C., Delmas, R., Dumestre, J.-F., and Richard, S.: Evolution temporelle des émissions gazeuses et des profils de gaz dissous Estimation du bilan de carbone de la retenue de Petit-Saut deux ans après sa mise en eau, Hydroécol. Appl., 9, 85-114, 1997a.

877 Galy-Lacaux, C., Delmas, R., Jambert, C., Dumestre, J. F., Labroue, L., Richard, S., and
878 Gosse, P.: Gaseous emissions and oxygen consumption in hydroelectric dams: A case study in
879 French Guyana, Global Biogeochem. Cycles, 11, 471-483, 1997b.

880 Gudasz, C., Bastviken, D., Steger, K., Premke, K., Sobek, S., and Tranvik, L. J.:
881 Temperature-controlled organic carbon mineralization in lake sediments, Nature, 466, 478-
882 481, 2010.

883 Guenet, B., Danger, M., Abbadie, L., and Lacroix, G.: Priming effect: bridging the gap
884 between terrestrial and aquatic ecology, Ecology, 91, 2850-2861, 10.1890/09-1968.1, 2010.

885 Guérin, F., Abril, G., Richard, S., Burban, B., Reynouard, C., Seyler, P., and Delmas, R.:
886 Methane and carbon dioxide emissions from tropical reservoirs: Significance of downstream
887 rivers, Geophys. Res. Lett., 33, 10.1029/2006gl027929, 2006.

888 Guérin, F., and Abril, G.: Significance of pelagic aerobic methane oxidation in the methane
889 and carbon budget of a tropical reservoir, Journal of Geophysical Research: Biogeosciences,
890 112, G03006, 10.1029/2006JG000393, 2007.

891 Guérin, F., Abril, G., Serça, D., Delon, C., Richard, S., Delmas, R., Tremblay, A., and
892 Varfalvy, L.: Gas transfer velocities of CO_2 and CH_4 in a tropical reservoir and its river
893 downstream, Journal of Marine Systems, 66, 161-172, 2007.

894 Guérin, F., Abril, G., de Junet, A., and Bonnet, M.-P.: Anaerobic decomposition of tropical
895 soils and plant material: Implication for the CO2 and CH4 budget of the Petit Saut Reservoir,
896 Appl. Geochem., 23, 2272-2283, 10.1016/j.apgeochem.2008.04.001, 2008.

897 Guérin, F., Deshmukh, C., Labat, D., Pighini, S., Vongkhamsao, A., Guédant, P., Rode, W.,
898 Godon, A., Chanudet, V., Descloux, S., and Serça, D.: Effect of sporadic destratification,
899 seasonal overturn, and artificial mixing on CH4 emissions from a subtropical hydroelectric
900 reservoir, Biogeosciences, 13, 3647-3663, 10.5194/bg-13-3647-2016, 2016.

901 Kemenes, A., Forsberg, B. R., and Melack, J. M.: CO2 emissions from a tropical
902 hydroelectric reservoir (Balbina, Brazil), J. Geophys. Res., 116, G03004,
903 10.1029/2010jg001465, 2011.

904 Li, Z., Zhang, Z., Lin, C., Chen, Y., Wen, A., and Fang, F.: Soil–air greenhouse gas fluxes
905 influenced by farming practices in reservoir drawdown area: A case at the Three Gorges
906 Reservoir in China, Journal of Environmental Management, 181, 64-73,
907 http://dx.doi.org/10.1016/j.jenvman.2016.05.080, 2016.

908 Lovatt Smith, P. F., Stokes, R. B., Bristow, C., and Carter, A.: Mid-Cretaceous inversion in
909 the Northern Khorat Plateau of Lao PDR and Thailand, Geological Society, London, Special
910 Publications, 106, 233-247, 10.1144/gsl.sp.1996.106.01.15, 1996.

911 MacIntyre, S., Jonsson, A., Jansson, M., Aberg, J., Turney, D. E., and Miller, S. D.: Buoyancy
912 flux, turbulence, and the gas transfer coefficient in a stratified lake, Geophys. Res. Lett., 37,
913 L24604, 10.1029/2010GL044164, 2010.

914 Marotta, H., Pinho, L., Gudasz, C., Bastviken, D., Tranvik, L. J., and Enrich-Prast, A.:
915 Greenhouse gas production in low-latitude lake sediments responds strongly to warming,
916 Nature Clim. Change, 4, 467-470, 10.1038/nclimate2222, 2014.

917 Pacheco, F. S., Soares, M. C. S., Assireu, A. T., Curtarelli, M. P., Roland, F., Abril, G., Stech,
918 J. L., Alvalá, P. C., and Ometto, J. P.: The effects of river inflow and retention time on the
919 spatial heterogeneity of chlorophyll and water–air CO2 fluxes in a tropical hydropower
920 reservoir, Biogeosciences, 12, 147-162, 10.5194/bg-12-147-2015, 2015.

Panneer Selvam, B., Natchimuthu, S., Arunachalam, L., and Bastviken, D.: Methane and carbon dioxide emissions from inland waters in India – implications for large scale greenhouse gas balances, Global Change Biology, n/a-n/a, 10.1111/gcb.12575, 2014.

Prairie, Y. T., Alm, J., Beaulieu, J., Barros, N., Battin, T., Cole, J., del Giorgio, P., DelSontro, T., Guérin, F., Harby, A., Harrison, J., Mercier-Blais, S., Serça, D., Sobek, S., and Vachon, D.: Greenhouse Gas Emissions from Freshwater Reservoirs: What Does the Atmosphere See?, Ecosystems, 10.1007/s10021-017-0198-9, 2017.

Raymond, P. A., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., Butman, D., Striegl, R., Mayorga, E., Humborg, C., Kortelainen, P., Durr, H., Meybeck, M., Ciais, P., and Guth, P.: Global carbon dioxide emissions from inland waters, Nature, 503, 355-359, 2013.

Roehm, C., and Tremblay, A.: Role of turbines in the carbon dioxide emissions from two boreal reservoirs, Quebec, Canada, Journal of Geophysical Research-Atmospheres, 111, D24101, 10.1029/2006jd007292, 2006.

Roland, F., Vidal, L. O., Pacheco, F. S., Barros, N. O., Assireu, A., Ometto, J., Cimbleris, A. C. P., and Cole, J. J.: Variability of carbon dioxide flux from tropical (Cerrado) hydroelectric reservoirs, Aquatic Sciences, 72, 283-293, 10.1007/s00027-010-0140-0, 2010.

Sabater, F., Butturini, A., MartÍ, E., Muñoz, I., Romaní, A., Wray, J., and Sabater, S.: Effects of riparian vegetation removal on nutrient retention in a Mediterranean stream, Journal of the North American Benthological Society, 19, 609-620, 10.2307/1468120, 2000.

Serça, D., Delmas, R., Jambert, C., and Labroue, L.: Emissions of nitrogen oxides from equatorial rain forest in central Africa, Tellus B, 46, 10.3402/tellusb.v46i4.15795, 1994.

Serça, D., Deshmukh, C., Pighini, S., Oudone, P., Vongkhamsao, A., Guédant, P., Rode, W., Godon, A., Chanudet, V., Descloux, S., and Guérin, F.: Nam Theun 2 Reservoir four years after commissioning: significance of drawdown methane emissions and other pathways, Hydroécol. Appl., 19, 119-146, 2016.

Smith, L. K., Lewis, W. M., Chanton, J. P., Cronin, G., and Hamilton, S. K.: Methane emissions from the Orinoco River floodplain, Venezuela, Biogeochemistry, 51, 113-140, 10.1023/a:1006443429909, 2000.

Smith, P. F. L., and Stokes, R. B.: GEOLOGY AND PETROLEUM POTENTIAL OF THE KHORAT PLATEAU BASIN IN THE VIENTIANE AREA OF LAO P.D.R, Journal of Petroleum Geology, 20, 27-49, 10.1111/j.1747-5457.1997.tb00754.x, 1997.

Sobek, S., Tranvik, L. J., and Cole, J. J.: Temperature independence of carbon dioxide supersaturation in global lakes, Glob. Biogeochem. Cycle, 19, GB2003, 10.1029/2004gb002264, 2005.

St Louis, V. L., Kelly, C. A., Duchemin, E., Rudd, J. W. M., and Rosenberg, D. M.: Reservoir surfaces as sources of greenhouse gases to the atmosphere: A global estimate, Bioscience, 50, 766-775, 2000.

Tadonléké, R. D., Marty, J., and Planas, D.: Assessing factors underlying variation of CO2 emissions in boreal lakes vs. reservoirs, FEMS Microbiology Ecology, 79, 282-297, 10.1111/j.1574-6941.2011.01218.x, 2012.

Teodoru, C. R., Prairie, Y. T., and del Giorgio, P. A.: Spatial Heterogeneity of Surface CO2 Fluxes in a Newly Created Eastmain-1 Reservoir in Northern Quebec, Canada, Ecosystems, 14, 28-46, 10.1007/s10021-010-9393-7, 2011.

965 Teodoru, C. R., Bastien, J., Bonneville, M.-C., del Giorgio, P. A., Demarty, M., Garneau, M.,
966 Hélie, J.-F., Pelletier, L., Prairie, Y. T., Roulet, N. T., Strachan, I. B., and Tremblay, A.: The
967 net carbon footprint of a newly created boreal hydroelectric reservoir, Global Biogeochem.
968 Cycles, 26, GB2016, 10.1029/2011gb004187, 2012.

969 Wang, F., Wang, B., Liu, C.-Q., Wang, Y., Guan, J., Liu, X., and Yu, Y.: Carbon dioxide
970 emission from surface water in cascade reservoirs–river system on the Maotiao River,
971 southwest of China, Atmospheric Environment, 45, 3827-3834,
972 http://dx.doi.org/10.1016/j.atmosenv.2011.04.014, 2011.

973 Watts, C. J.: Seasonal phosphorus release from exposed, re-inundated littoral sediments of
974 two Australian reservoirs, Hydrobiologia, 431, 27-39, 10.1023/a:1004098120517, 2000.

975 Weiss, R. F.: Carbon dioxide in water and seawater: the solubility of a non-ideal gas, Marine
976 Chemistry, 2, 203-215, http://dx.doi.org/10.1016/0304-4203(74)90015-2, 1974.

977 Xiao, S., Wang, Y., Liu, D., Yang, Z., Lei, D., and Zhang, C.: Diel and seasonal variation of
978 methane and carbon dioxide fluxes at Site Guojiaba, the Three Gorges Reservoir, Journal of
979 Environmental Sciences, 25, 2065-2071, http://dx.doi.org/10.1016/S1001-0742(12)60269-1,
980 2013.

981 Yang, L., Lu, F., Wang, X., Duan, X., Song, W., Sun, B., Chen, S., Zhang, Q., Hou, P.,
982 Zheng, F., Zhang, Y., Zhou, X., Zhou, Y., and Ouyang, Z.: Surface methane emissions from
983 different land use types during various water levels in three major drawdown areas of the
984 Three Gorges Reservoir, Journal of Geophysical Research: Atmospheres, 117, D10109,
985 10.1029/2011JD017362, 2012.

986 Yang, L., Lu, F., Wang, X., Duan, X., Tong, L., Ouyang, Z., and Li, H.: Spatial and seasonal
987 variability of CO2 flux at the air-water interface of the Three Gorges Reservoir, Journal of
988 Environmental Sciences, 25, 2229-2238, http://dx.doi.org/10.1016/S1001-0742(12)60291-5,
989 2013.

990 Yvon-Durocher, G., Allen, A. P., Bastviken, D., Conrad, R., Gudasz, C., St-Pierre, A., Thanh-
991 Duc, N., and del Giorgio, P. A.: Methane fluxes show consistent temperature dependence
992 across microbial to ecosystem scales, Nature, 507, 488-491, 10.1038/nature13164, 2014.

993 Zhao, Y., Wu, B. F., and Zeng, Y.: Spatial and temporal patterns of greenhouse gas emissions
994 from Three Gorges Reservoir of China, Biogeosciences, 10, 1219-1230, 10.5194/bg-10-1219-
995 2013, 2013.

996

997

Table 1 : Soil type and characteristics at the sampling station of the drawdown area of the Nam Theun 2 Reservoir (Lao PDR). KKK formation.

Catena	solum	%N	%C	C:N	pH	Soil name WRB FAO	Soil texture	lithology
MNR	MNR upland	0.11	1.47	13.69±1.73	4.33	planosol	sandy	Micaceous
	MNR interm. down	0.10	1.32	13.55±1.84		endogleyic planosol		quartzose
	MNR shoreline	0.13	1.89	14.78±1.60	4.23	gleysol		
RES3S	RES3 upland	0.18	2.38	13.21±0.63	4.18	plinthosol	clay	Red mudstone
	RES3 interm.					etagnic plinthosol		
	RES3 shoreline	0.17	1.95	11.21±0.56	4.88	plinthic stagnosol		
RES2S	RES2 upland	0.16	2.24	13.62±0.60		plinthic ferralsol	sandy clay	Micaceous
	RES2 interm.	0.20	2.30	11.25±0.50		« stagnic » ferralsol		sandstone
	RES2 shoreline	0.13	1.41	10.55±0.54		stagnosol		
RES8S	RES8 upland	0.08	1.76	23.47±3.95		acrisol	sandy clay	Quaternary deposits
	RES8 interm. up	0.06	0.68	11.93±1.46		stagnic acrisol		
	RES8 interm. down	0.09	1.31	13.99±1.99		stagnic acrisol		
	RES8 shoreline	0.12	2.02	17.07±1.93		endogleyic stagnosol		
RES8'S	RES8' upland	0.05	0.77	16.15±2.30		acrisol	sandy clay	Quaternary deposits
	RES8' shoreline	0.08	1.51	18.22±2.79		endogleyic stagnosol		
RES4S	RES4 upland	0.16	1.98	12.76±1.17	4.14	acrisol	sandy clay	Micaceous
	RES4 interm. up	0.13	1.92	14.66±1.58		stagnic acrisol		sandstone
	RES4 interm. down	0.12	1.67	14.33±1.71		stagnic acrisol		
	RES4 shoreline	0.10	1.36	14.35±1.97	4 .44	gleysol		

Mis en forme

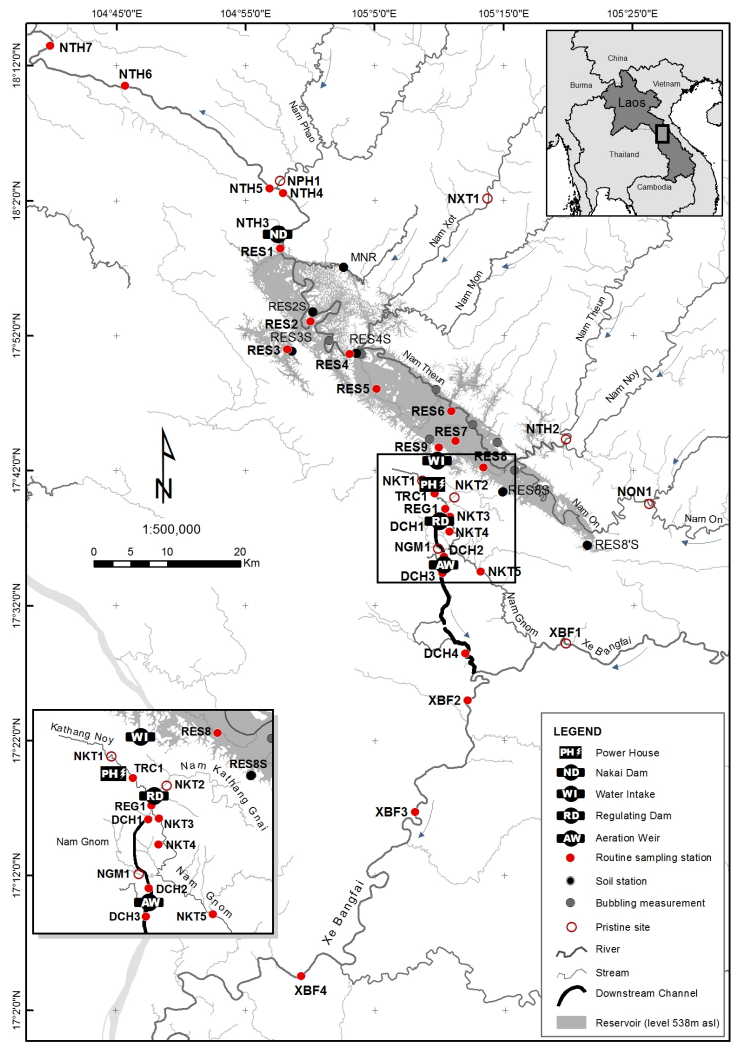
Table 2 Temperature (°C), relative humidity (%) and CO_2 fluxes (mmol m^{-2} d^{-1}) from the soils of the drawdown area of the Nam Theun 2 Reservoir (Lao PDR).

	2010			2011			2013		
Site	Hum	Temp	CO_2 flux	Hum	Temp	CO_2 flux	Hum	Temp	CO_2 flux
MNR upland	17.5	25.7	265±37	18.3	24.4	328±43			
MNR interm. up				26.9	27.5	669±56			
MNR interm. down	19.6	32.3	201±19	23.7	29	251±99			
MNR shoreline	37	31.9	40	46.4	27.3	67±7			
RES3S upland	22.3	26.8	231	23.6	25.6	366±14			
RES3S interm.	49.5	27.4	184±50	30.2	26.1	186±57			
RES3 Sshoreline	42.3	28.3	503±97	25.6	19.8	391±23			
RES2S upland	19.9	26.4	183±1	24.5	25.2	531±41			
RES2S interm.	34.6	29.2	138±21	30.2	26.1	339±52			
RES2S shoreline	49.4	28.5	332±5	48.7	27.1	166±23			
RES8S upland	27.7	28.2	86±0	26.9	27.0	468			
RES8S interm. up	32.3	28.3	75±15	33.2	26.9	300±19			
RES8S interm. down	32.9	29.1	110±10	32.3	27.8	239±44			
RES8S shoreline	45.3	29.7	286±59	44.5	28.5	660±121			
RES8S' upland	32.6	32.5	342±70						
RES8S' interm.	35.9	31.9	143±24						
RES8S'shoreline	42.7	31.9	34±7						
RES4S upland	26.7	28.6	326±20	21.7	29.5	526±35	18.1	31.1	232±50
RES4S interm. up							24.3	28.7	196±29
RES4S interm. down	26.0	34.2	168±28	21.8	32.7	619±39	35.1	29.8	443±67
RES4S shoreline	44.6	31.1	34±7	18.3	32.1	115	51.2	29.6	393±57

Table 3: CO_2 emissions (in $GgCO_2.year^{-1}$) from the Nam Theun 2 Reservoir (Lao PDR) for the first five years after impoundment (2009, 2010, 2011, 2012 and 2013). Percentages between brackets represent the proportion of each component to the total annual emission.

Year	Ebullition	Diffusion (Reservoir)	Diffusion (Drawdown)	Degassing	Diffusion (Downstream)	**Total**
2009	1.2±0.5 **(<1%)**	730.0±46.2 **(92%)**	6.3±0.5 **(1%)**	52.7±14.9 **(7%)**	4.0±0.3 **(<1%)**	**794.1±48.5**
2010	1.04±0.5 **(<1%)**	538.57±28.6 **(51%)**	413.7±15.9 **(39%)**	85.37±17.4 **(8%)**	14.34±0.4 **(1%)**	**1053.0±37.0**
2011	1.06±0.5 **(<1%)**	345.88±24.3 **(42%)**	386.4±16.0 **(47%)**	84.03±10.7 **(10%)**	11.60±0.5 **(1%)**	**828.9±31.0**
2012	0.95±0.4 **(<1%)**	173.30±11.5 **(23%)**	572.3±19.9 **(75%)**	17.03±3.8 **(2%)**	2.23±0.2 **(<1%)**	**765.8±23.3**
2013	1.04±0.5 **(<1%)**	118.70±27.3 **(21%)**	419±15.0 **(76%)**	13.61±4.0 **(2%)**	1.43±0.2 **(<1%)**	**553.8±31.4**

Figure 1 Map of the Nam Theun 2 monitoring network. The station names are defined by numbers and an abbreviated name as follow: RES standing for reservoir, NTH for Nam Theun River, NON for Nam On River, NXT for Nam Xot, NPH1 for Nam Phao River, TRC for Tail Race Channel, REG for Regulatin Pond, DCH for downstream channel, NKT for Nam Katang River, NGM for Nam Gnom and XBF for Xe Bangfai River.



Mis en forme

Supprimé:

Figure 2 : Median and interquartile range (boxes), average (+), and full range of values (whiskers) of particulate organic carbon (POC), dissolved organic carbon (DOC), total inorganic carbon (TIC) and CO2 concentrations in four pristine river of the Nam Theun watershed during three distinct seasons : cold dry (CD), warm dry (WD) and warm wet (WW) seasons. The dataset includes data from 2009 to 2013.

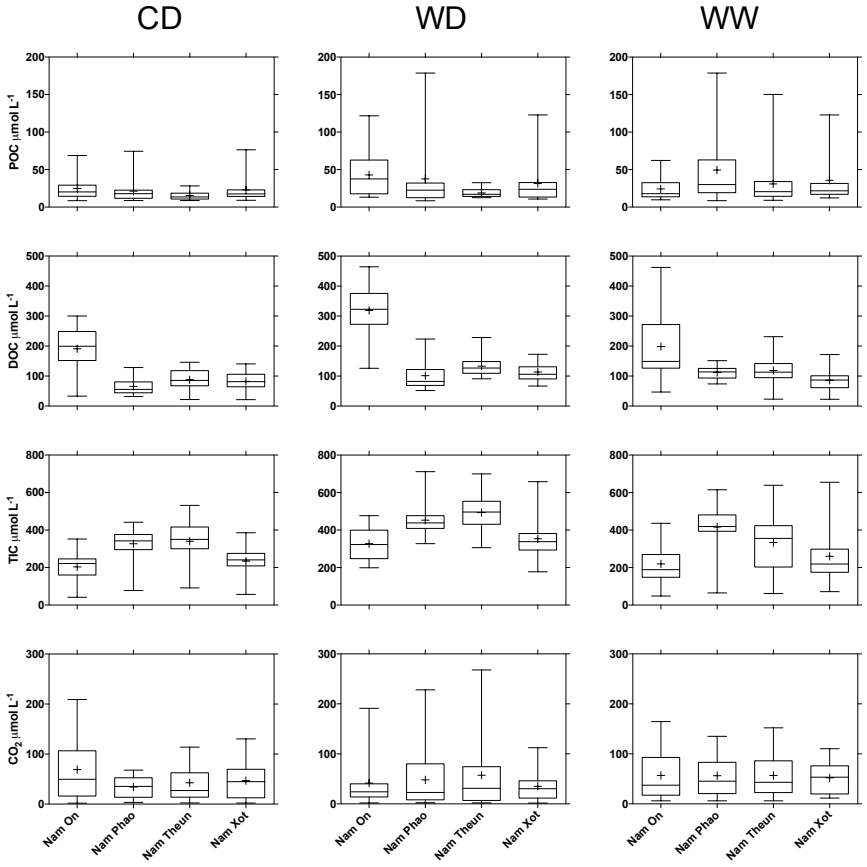


Figure 3: Total carbon inputs in form of particulate organic carbon (POC), dissolved organic carbon (DOC) and total inorganic carbon (TIC) from the Nam Theun watershed to the Nam Theun 2 Reservoir for four distinct years after reservoir impoundment.

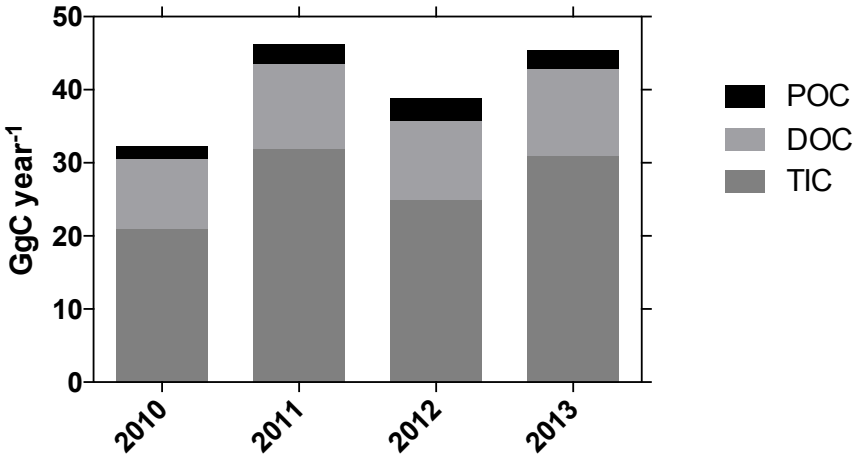


Figure 4: Temperature (grey solid circle) and oxygen (black solid circle), DOC (open square), POC (solid square) and CO_2(triangle) concentrations in the Nam Theun 2 Reservoir water column during the cool dry, warm dry and warm wet seasons in 2011 at three stations (RES3, RES7 and RES9).

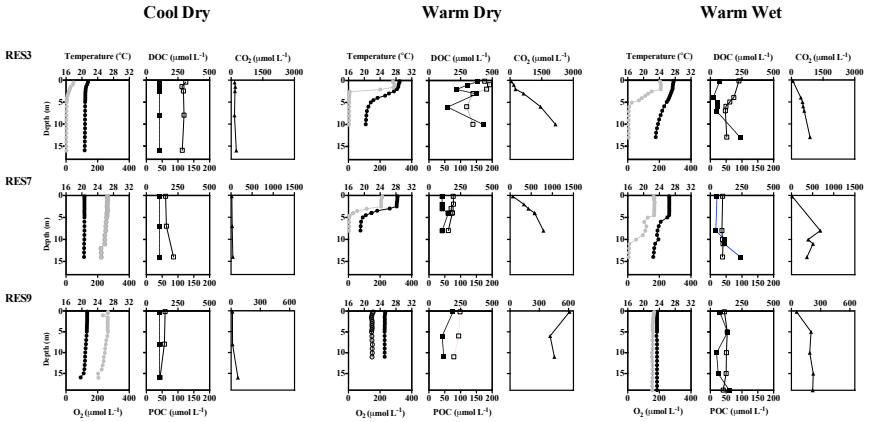


Figure 5: Monthly average CO_2 concentrations at the stations RES1-8 (a) and at the station RES9 (b), average diffusive fluxes at the stations RES1-8 (c) and at the station RES9 (d) and total monthly (e) and yearly (f) CO_2 emissions by diffusive fluxes from the Nam Theun 2 Reservoir (Lao PDR)

Supprimé: (a)

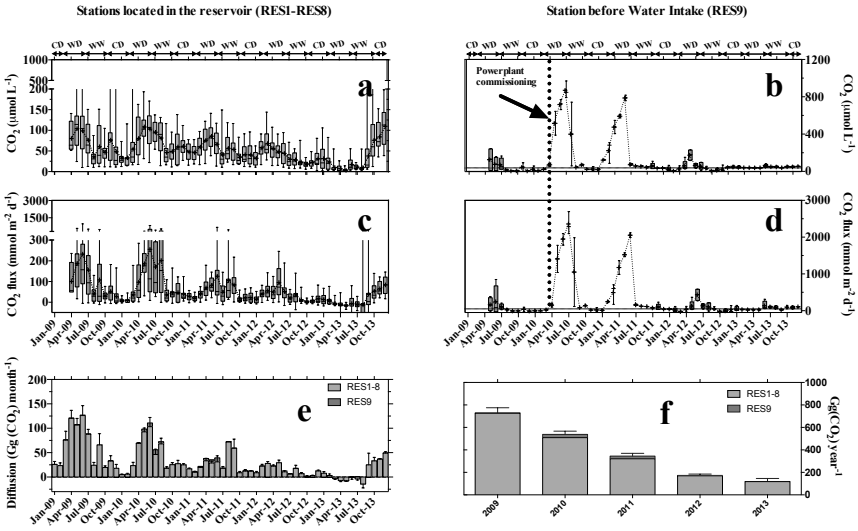


Figure 6: Diffusive fluxes and degassing below the powerhouse and the Nakai Dam on a monthly (a) and yearly basis (b) at the Nam Theun 2 Reservoir (Lao PDR). Note that degassing below ND includes spillway release (main contributor to 2009 and 2011 emissions below ND). Degassing below the powerhouse includes degassing immediately downstream of the turbines, downstream of the regulation dam and downstream of the aeration.

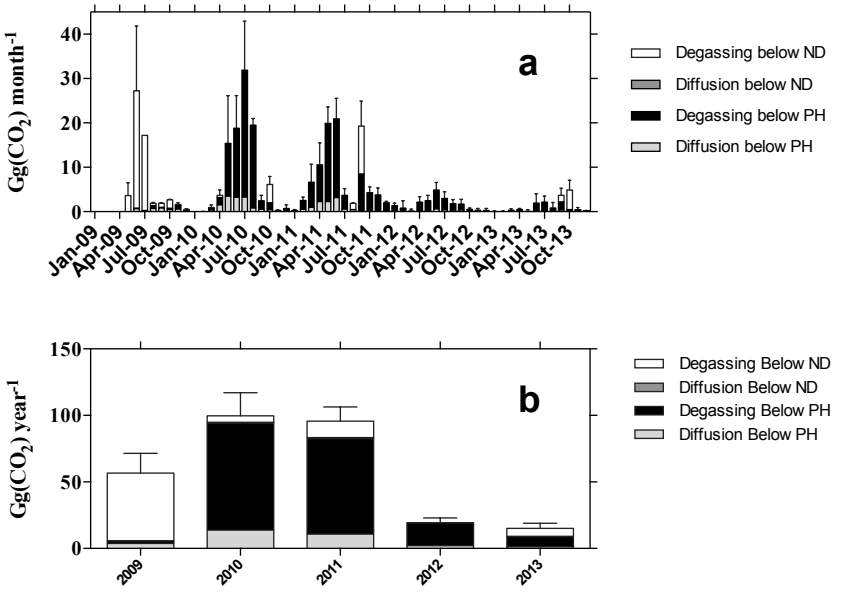


Figure 7: Monthly emissions from the drawdown area and variation of the area of the drawdown area of the Nam Theun 2 Reservoir (Lao PDR)

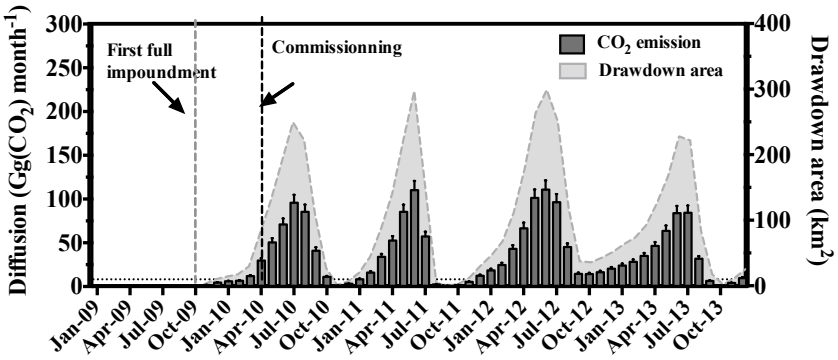


Figure 8: Monthly (a) and yearly (b) average of the total emissions from the Nam Theun 2 Reservoir by diffusion at the reservoir surface, diffusion from the drawdown area, ebullition, degassing and diffusion from the Nam Theun River and artificial channel at the Nam Theun 2 Reservoir (Lao PDR). On panel a, water level variations in the reservoir are given.