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

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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 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 four rivers of the Nam Theun watershed at nine 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 2012-2013. 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 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. 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.

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.

Recently, the importance of the drawdown emissions was pointed out as a significant source of CH_4 in the Three Gorges Dam (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 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.

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2 Material and Methods

2.1 Study site

The NT2R is located in Lao People Democratic Republic's (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 details 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 decreased down to 170 km^2 in the 2011 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^{-2} whereas the driest year was 2012 with a discharge 230 m^3 s^{-2}. 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 released to the powerhouse, the regulating pond and finally the artificial downstream channel before water reaches the Xe Bangfai River (Figure 1).

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2.2 Sampling strategy

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

2.3 In situ measurements and water analysis

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

148 samples for calibration. Detection limit was < 1 ppmv in headspace and duplicate injection of
149 samples showed reproducibility better than 5%. For TIC, DOC and POC, analyses were
150 performed with a Shimadzu TOC-V_{CSH} analyser. Filtered (0.45 µm, Nylon) and unfiltered
151 samples were analysed for TIC and TOC. POC was calculated by the difference between
152 TOC and DOC concentrations in unfiltered and filtered samples. The detection limit was 8
153 µmol L^{-1} and uncertainty was 2.0 µmol L^{-1} on TOC and DOC and 2.8 µmol L^{-1} on POC.

154 **2.4 Organic and inorganic carbon inputs from the watershed to the reservoir**

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

166 **2.5 Diffusive fluxes and degassing**

167 Diffusive fluxes at the air-water interface of the reservoir were calculated from the surface
168 CO_2 concentrations, wind speed and rainfall rates using the gas transfer velocity formulations
169 of Guérin et al. (2007) and MacIntyre et al. (2010) as already described for CH_4 fluxes from
170 this reservoir (Deshmukh et al., 2014;Guérin et al., 2016). Based on physical modelling and in
171 situ measurements (Chanudet et al., 2012), we determined that the station RES9 located at the
172 water intake is representative of an area of about 3 km^2 (i.e. 0.6 % of the reservoir water
173 surface at full reservoir water supply), whatever the season (Guérin et al., 2016). This area
174 was therefore used to extrapolate specific diffusive fluxes from this station. For other stations,
175 diffusive fluxes are calculated with the daily meteorological parameters and reservoir water
176 surface area from the capacity curve. Degassing downstream of the powerhouse, the
177 regulating dam and the aeration weir, all located along the artificial channel and downstream
178 of the Nakai Dam (Figure 1), were computed using the CO_2 concentration upstream and

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179 downstream of these civil structures and the water discharge as in Deshmukh et al. (2016) for
180 CH_4. The diffusion from the rivers and artificial channel below the powerhouse and the dam
181 was calculated using a constant gas transfer velocity of 10 cm h^{-1} (Deshmukh et al., 2016).

182 **2.6 CO_2 bubbling**

183 Bubbling of CO_2 was determined with funnels (Deshmukh et al., 2014) during five field
184 campaigns covering different seasons (between May 2009 and June 2011), and during a
185 weekly monitoring from March 2012 to August 2013. During this monitoring, spatial
186 variation was explored through measurements spread over six stations (Fig. 1) representative
187 of the different types of flooded ecosystems (dense and medium forests, light and degraded
188 forest and agricultural lands as determined by Descloux et al. (2011)), and with different
189 depths (from 0.4 to 16 m) at each station. We stopped measuring bubbling at sites deeper than
190 16m after no ebullition was observed during the first three campaigns. Bubble samples were
191 taken with a 50 mL-syringe and the syringe was immediately connected to a N_2-preflushed
192 10-mL serum vial, leading to a dilution factor of 5/6 (Guérin et al., 2007). Gas samples were
193 analysed with the GC described above.

194 **2.7 Soil descriptions and CO_2 fluxes from the drawdown area**

195 Since the drawdown area of the NT2R could represent up to 65% of the surface area of the
196 reservoir at the end of the WD season, emissions from this major area under the influence of
197 flooding were evaluated. Soils types were determined together with CO_2 emissions. Soil
198 description was carried out in June 2010 at 6 sites and soils from the station RES4S plot were
199 characterized in details in June 2013 (Figure 1, Table 1). Four sites were selected in the Nam
200 Theun River riparian's area (NMR, RES2S, RES4S, RES8S'), one site in the flooded primary
201 forest (RES3S) and one site in the flooded agricultural area (RES8S). Soil study was
202 conducted through soil catenae of 2 to 4 soils profiles from the pristine soils on top ("upland"
203 samples) to the shoreline of the reservoir ("shoreline" samples). One or two other soils
204 profiles were performed in between ("interm.up" and "interm.down" samples). Soil sampling
205 was performed with an Edelman soil corer down to a depth of 1m, but only 0-20cm depth
206 samples were considered in this study. Information on horizon depth, soil texture and
207 structure (e.g., compactness, porosity), color (Munssel chart for soil color), soil fauna activity
208 and pedological features (e.g., redoximorphic features, concretions) were provided through
209 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 subsample 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, 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, 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 details 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, 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%) than in 2010 and 2012 (56±3%). In 2013, which was an average hydrological year, the the water column was well oxygenated with 71±1% suggesting of improvement of the

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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.

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 CO2 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.

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-fivefold 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 a 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 to 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).

3.4 O_2, 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.

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

378 Immediately downstream of the Nakai Dam (NTH3) after the commissioning, the average O_2
379 concentration was 224 µmol L^{-1}, that is 87% saturation (n=73), and the concentration
380 increased further downstream. pH was 6.84±0.06 (n=166). Average DOC concentration was
381 166±2 µmol L^{-1} (n=653) and decreased from 197±4 µmol L^{-1} in 2010 (n=147) to 162±3 µmol
382 L^{-1} (n=127) in 2013. The average POC concentration was 50±5 µmol L^{-1} (n=7) and CO_2
383 concentration was 67±9 µmol L^{-1} (n=77). The CO_2 concentration decreased by a factor of two
384 (40±5 µmol L^{-1}, n=54) within the next 10 km below the dam (down to NTH4, Figure 1) where
385 pH was 7.19±0.06 (n=97). At NTH4, the observed concentrations were in the same order of
386 magnitude than the concentrations in the pristine rivers in the same watershed (53±6 µmol L^{-1}
387 at NPH1 in the Nam Phao River, n=59).

388 ### 3.5 CO_2 emissions downstream of the reservoir

389 After the commissioning, the annual average diffusive fluxes downstream of the powerhouse
390 decreased from 482±603 mmol m^{-2} d^{-1} in the year 2010 (-32-33762 mmol m^{-2} d^{-1}) to 32±8
391 mmol m^{-2} d^{-1} (-39-216 mmol m^{-2} d^{-1}) in 2013 (not show). They followed the same seasonal
392 dynamics as the CO_2 concentrations and they decrease with the distance from the

393 powerhouse. Total emissions by diffusion from the downstream channel decreased from
394 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
395 the whole downstream channel (including degassing below the turbines, the regulating pond
396 and the aeration weir) reached up to 28.5 Gg(CO_2) month^{-1} just after the commissioning of the
397 reservoir when the water was released for the first time (Figure 6a). During the monitoring,
398 60-90% of the annual degassing occurred within 3-4 months of transition between the WD
399 and WW seasons corresponding to the seasons when the hypolimnic waters were the most
400 enriched in CO_2 (Figure 6a). Total degassing decreased from 80±36 Gg(CO_2) year^{-1} in 2010
401 to 8±4 Gg(CO_2) year^{-1} in 2013 (Figure 6b).

402 Disregarding periods of spillway releases from April to June 2009 for water level regulation
403 and in September-October 2011 during the flood, degassing downstream of the Nakai Dam
404 (up to 0.48 Gg(CO_2) month^{-1}) is usually 10 times lower than degassing in the downstream
405 channel because of (1) the low continuous water discharge at the Nakai Dam (2 m^3 s^{-1}) and
406 (2) the withdrawal of the water from the reservoir epilimnion (Deshmukh et al., 2016) (Figure
407 6a). However, during the use of spillways for water level regulation in the reservoir,
408 degassing reached up to 26 Gg(CO_2) month^{-1} in 2009 before the commissioning and 4 to 10
409 Gg(CO_2) month^{-1} during the occasional uses in October 2010 and September 2011 (Figure
410 6a). As determined from the longitudinal profiles of CO_2 concentrations downstream of the
411 dam, diffusive emissions from the Nam Theun River that are actually attributable to the
412 NT2R occurred within the first 10 km below the dam as it was also the case for CH_4
413 (Deshmukh et al., 2016). The annual average diffusive CO_2 fluxes were 126±137 and
414 288±346 mmol m^{-2} d^{-1} in 2010 and 2011 respectively. The annual average diffusive CO_2 flux
415 was one order of magnitude lower in 2013 (24±68 mmol m^{-2} d^{-1}) (not show). The total
416 emissions by diffusion and degassing resulting from these fluxes ranged between 5.5±0.1
417 Gg(CO_2) year^{-1} in 2010 and 0.14±0.06 Gg(CO_2) year^{-1} in 2013 (Figure 6b).

418 On a yearly basis, emissions downstream of NT2R decreased from 99.7±25.3 to 15.0±6.5
419 Gg(CO_2) y^{-1} between 2010 and 2013 (Figure 6d). Before the reservoir commissioning in
420 2009, emissions were dominated by degassing due to spillway releases. After the
421 commissioning, emissions were dominated by degassing in the downstream channel which
422 contributed 80-90% of total downstream emissions.

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3.6 CO_2 bubbling

The CO_2 content in the sampled bubbles was 0.29±0.37% (n=2334) and no bubbles was ever observed for depth higher than 16 m. On average, the CO_2 bubbling was 0.16 ± 0.24 mmol m^{-2} d^{-1} (0-2.8 mmol m^{-2} d^{-1}). 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 ranging from 17.5 to 51.2% and temperature ranging from 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=0.452). Without significant spatial variations related to topography, humidity or temperature, we further consider the average of all fluxes that is 279±27 mmol m^{-2} d^{-1}.

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 could reach up to 110.8±10.7 Gg(CO_2) $month^{-1}$ by the end of the WD season when drawdown area reaches 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 reaches 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). The lowest emissions from the drawdown area occurred during

454 the wet year 2011 (386±16 Gg(CO_2) year^{-1}) and the highest emissions during the dry year
455 2012 (572±20 Gg(CO_2) year^{-1}).On average from 2009 to 2013, emissions from the drawdown
456 area was 431±42 Gg(CO_2) year^{-1}.

457 ## 4 Discussion

458 ### 4.1 CO_2 dynamic in the NT2R water column and downstream rivers

459 The dynamics of CO_2 in the NT2R is highly dependent on the hydrology and hydrodynamics
460 of the reservoir as it has already been described for CH_4 (Guérin et al., 2016). During the
461 warm seasons (WD and WW) when the water column is thermally stratified, the vertical
462 profiles of CO_2 concentration in the water column are similar to profiles obtained in other
463 tropical or subtropical reservoirs (Abril et al., 2005;Guérin et al., 2006;Kemenes et al.,
464 2011;Chanudet et al., 2011) but also boreal reservoirs (Demarty et al., 2011). The high
465 concentrations measured in the hypolimnion suggest that the main source of CO_2 is located at
466 the bottom and very likely in the flooded soils, vegetation and sediments whereas the decrease
467 of CO_2 toward the surface suggest both consumption by primary production and/or loss to the
468 atmosphere (Galy-Lacaux et al., 1997b;St Louis et al., 2000;Abril et al., 2005;Guérin et al.,
469 2008;De Junet et al., 2009;Teodoru et al., 2011;Barros et al., 2011;Chanudet et al., 2011). In
470 the CD season, after the reservoir overturn, the average CO_2 concentration in the reservoir
471 water column decreases sharply (by 50% on average) and CO_2 concentration increases
472 regularly from the surface to the bottom of the water column. However, no CO_2 burst was
473 observed at the beginning of the CD season when the reservoir overturns. Therefore it is
474 reasonable to assume that the reservoir overturn has only a moderate impact on CO_2
475 emissions. This assumption is reinforce by the fact that during the same sampling, hot
476 moments of CH_4 emissions were captured (Guérin et al., 2016). As observed in most tropical
477 and subtropical reservoirs, the higher concentrations were observed during the warm seasons
478 (Abril et al., 2005;Kemenes et al., 2011;Chanudet et al., 2011) whereas the lowest were found
479 after reservoir overturn (Chanudet et al., 2011). A significant shift in the carbon
480 biogeochemical cycling occurred in the reservoir in 2013 with the reservoir water surface
481 becoming of CO_2 sink during the WD season and the beginning of the WW season (from
482 March to August). Although no major change was observed nutrient concentrations, the
483 number of phytoplanktonic cell was 50% higher in 2013 than 2012 (Unpublished, M Cottet
484 personal com.) indicating that primary production was significantly enhanced in 2013.
485 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 fuel 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 reservoir 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 RES6-8. This difference is attributed to both (1) the difference in carbon density at the bottom of the reservoir in those two contrasted areas in terms of submerged ecosystems (Descloux et al., 2011) (see section 4.3) and (2) the difference in terms of water residence time between those two zones (Guérin et al., 2016). Stations RES1-3 are located in areas with the longest water residence time in the reservoir since the water mostly enters the reservoir in the RES6-8 area from the Nam Theun, Nam Noy and Nam On Rivers before being delivered to the water intake (close to RES9) on the opposite side of NT2R which has a narrow and elongated shape (Figure 1). Therefore, the water renewal in the RES6-9 area is high and CO_2 accumulates less

517 in the water column confirming the importance of the reservoir hydrology on the spatial
518 variability of dissolved gases in reservoirs (Pacheco et al., 2015;Guérin et al., 2016).

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

530 Downstream of the reservoir in the Nam Theun River or the artificial channel, CO_2
531 concentrations follow the same seasonality as in the reservoir. Concentrations peak in June-
532 July at the transition between the WD and the WW season, and reach their minima in the CD
533 season. Downstream of the Nakai Dam, the concentrations are twice lower than downstream
534 of the powerhouse since mostly epilimnic water from the RES1 station is transferred
535 downstream of the dam. Within less than 10 km further downstream, concentrations are not
536 significantly higher than in pristine rivers of the watershed. Downstream of the powerhouse,
537 CO_2 concentrations in 2010 were in the same order of magnitude as in 10-20 years-old
538 reservoirs in South America flooding tropical forest (Abril et al., 2005;Guérin et al.,
539 2006;Kemenes et al., 2011) whereas four years after impoundment CO_2 concentrations were
540 two times lower than in 20-30 years-old reservoirs in Lao PDR (Chanudet et al., 2011). We
541 hypothesize that the low CO_2 concentration downstream of the NT2R result from a significant
542 degassing of the water at the water intake before the water is transferred downstream as
543 observed for CH_4 (Deshmukh et al., 2016;Guérin et al., 2016).

544 **4.2 Total CO_2 emissions from the Nam Theun 2 Reservoir**

545 From 2009 to 2013, total CO_2 emissions from NT2R show the same seasonal pattern (Figure
546 8a). The lowest total emissions occur in the CD season while the highest emissions occur at
547 the transition between the WD and the WW season when emissions by all individual

548 pathways reach their maximum. From 2010 to 2013, emissions at the transition between the
549 WD and the WW season between April and July contributed 47 to 61% of total emissions
550 suggesting that quantification of emissions based on two to four campaigns in a year might be
551 subject to caution since seasonality of emissions significantly affects emissions factors.

552 CO_2 bubbling follows the same seasonal variations, being triggered by water level and
553 concomitant hydrostatic decrease as for CH_4 (Chanton et al., 1989;Engle and Melack,
554 2000;Smith et al., 2000;Boles et al., 2001;Deshmukh et al., 2014) but its contribution is
555 negligible (<1%, Table 3). Low CO_2 emission by bubbling as also observed in temperate
556 reservoirs (Bevelhimer et al., 2016) is attributed to the higher solubility of CO_2 in water than
557 CH_4 which lead to the solubilisation of the majority of CO_2 as free CO_2 or as DIC.

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

568 Emissions by diffusive fluxes at the surface of the reservoir increase by a factor of two by the
569 end of the WD season (Figure 5a) compare to the CD season from 2009 to 2012. The average
570 CO_2 emissions in 2009 and 2010 and in a lesser extend 2011 are in the same range as
571 emissions from the Petit Saut Reservoir during the first five years after impoundment (Abril et
572 al., 2005) and in the upper range of average CO_2 diffusive fluxes measured in older tropical
573 reservoirs (dos Santos et al., 2006;Kemenes et al., 2011;Yang et al., 2013) or in young boreal
574 reservoirs (Teodoru et al., 2011;Tadonléké et al., 2012). In 2012 and 2013, emissions from
575 NT2R by diffusive fluxes are still higher than most of the older Asian reservoirs (Wang et al.,
576 2011;Chanudet et al., 2011;Zhao et al., 2013;Xiao et al., 2013;Panneer Selvam et al., 2014)
577 and other Brazilian reservoirs flooding savannah (Roland et al., 2010;Pacheco et al., 2015).
578 The low emissions in the CD season from the first 3.5 years might mostly result from lower
579 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 originate 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 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

613 further specific studies in these overlooked ecosystems. So far, we cannot predict future
614 evolution of CO_2 emissions in this area based on the available data. The consequence of the
615 flooding on the respiration rate of these soils may lead to a decrease of emissions with time or
616 a stabilization (see next section). Therefore, the net contribution of the drawdown zone to
617 emissions from the reservoir remains unclear and specifically requires research on soil OM
618 dynamics and would also require the inclusion of the vegetation dynamics when present.

619 This is the first comprehensive quantification of CO_2 emissions from a reservoir where all
620 known CO_2 pathways to the atmosphere were taking into account at one of the best spatial
621 and temporal resolution reported in the literature. We showed that downstream emissions and
622 emissions around the water intake are not negligible (~10% overall) and that the overlooked
623 drawdown area in CO_2 studies could be the main emission pathway of CO_2 to the atmosphere.
624 Overall, this study highlights that global estimate of CO_2 and CH_4 emissions from reservoir
625 are underestimated so far since relevant pathways like drawdown emissions in flat/shallow
626 reservoirs with large water level variations and downstream emissions in thermally stratified
627 reservoirs are missing in most site-specific studies used for extrapolations (Deemer et al.,
628 2016;Barros et al., 2011).

629 ### 4.3 Source of organic matter fuelling the reservoir CO_2 emissions

630 In tropical reservoirs, the decrease of the CO_2 concentration in the water column and
631 subsequent emissions with the age of the reservoir (Figure 8b) is supposed to result from the
632 decrease of the aerobic and anaerobic mineralisation rate due to the exhaustion of labile OM
633 from the pool of soil and vegetation that was flooded during impoundment (Abril et al.,
634 2005;Guérin et al., 2008). In boreal reservoirs, the decrease of benthic CO_2 production is
635 sharp and after 3-5 years, most of the CO_2 production appears to be pelagic and is supposed
636 not to result from the flooded organic matter (Teodoru et al., 2011;Brothers et al., 2012). The
637 total CO_2 emissions were nine and three times higher than the carbon inputs from the
638 watershed to the NT2R in 2010 (32 GgC yr^{-1}) and 2013 (45 GgC yr^{-1}), respectively (Figure 3
639 and Table 3). It has to be noted that interannual variations of carbon inputs to the NT2R
640 (Figure 3) are not correlated with the regular decrease of total CO_2 emissions from year to
641 year (Figure 8b). It is therefore unlikely that most of CO_2 emissions result from the
642 mineralization of allochthonous OM but rather from the contribution of the flooded carbon
643 pool (soil and vegetation) which amount is decreasing with time. This is consistent with the

644 fact that at Petit Saut, even 10 years after flooding, the majority of the OM in the water
645 column has a terrestrial origin (De Junet et al., 2009). According to Abril et al. (2005) at Petit
646 Saut, total emissions (disregarding drawdown emissions which were not measured) were 9 to
647 6 times higher than carbon inputs from the watershed during the first 4 years for similar
648 carbon inputs which indicates a faster decrease of emissions in NT2R than at Petit Saut. This
649 sharp decrease of emissions at NT2R might be due to the fact that the flooded pool of OM and
650 therefore the amount of labile OM in NT2R was twice smaller than the amount of OM
651 flooded in the Petit Saut (Guérin et al., 2008;Descloux et al., 2011). We show here, as it was
652 done at Petit Saut (Guérin et al., 2008;Abril et al., 2005), that external sources of carbon are
653 not sufficient to fuel the CO_2 emissions from the NT2R and we attribute the decrease of
654 emissions with time to the exhaustion of the most labile fraction of the flooded pool of OM
655 which might be the main source of reactive carbon in the reservoir.

656 In the sub-tropical NT2R, CO_2 concentrations are always higher at the bottom than in the
657 epilimnic waters even during the CD season when the limited thermal stratification or its
658 absence do not favour hypolimnic CO_2 accumulation. The CD season is probably the most
659 favourable season to pelagic respiration as this process is enhanced by the re-oxygenation of
660 the water column (Bastviken et al., 2004). Since CO_2 concentration in the CD season is 50%
661 lower than in the warm seasons, we suggest that CO_2 is mostly produced in the sediment and
662 flooded soils and vegetation. Disregarding the station RES9 located at the water intake,
663 significant spatial variation of CO_2 hypolimnic concentrations were found between stations
664 located in the area of dense forest (RES1-3) versus stations located in areas close to the three
665 main tributaries (RES6-8). Stations RES1-3 which have the highest average bottom
666 concentrations are located in areas where the carbon density is 50% higher than the
667 agricultural ecosystems that were flooded in the area of the stations RES6-8 (Descloux et al.,
668 2011).

669 In the absence of significant vegetation regrowth in the drawdown area during the study
670 period, the main source of carbon fuelling emissions from the drawdown area are not clearly
671 identified. Immediately after flooding, the most labile part of the soil OM and the
672 decomposing vegetation must have been the main sources of C fuelling the emissions. On the
673 long haul, the atmospheric carbon sink associated with the pristine vegetation dynamics has
674 been lost but as a consequence, the loss of this vegetation which might reduce labile OM
675 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 and 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 algaes 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 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 tropical reservoir starting less than a year after reservoir impoundment and lasting 4.5 years. This estimation includes all 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 with time over the years coupled with the fact that the incoming flux of carbon from the watershed to the reservoir represent 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.

We found that gross CO_2 emissions from the drawdown area represented up to 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.

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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		

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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

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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**

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Figure 1 Map of the Nam Theun 2 monitoring network

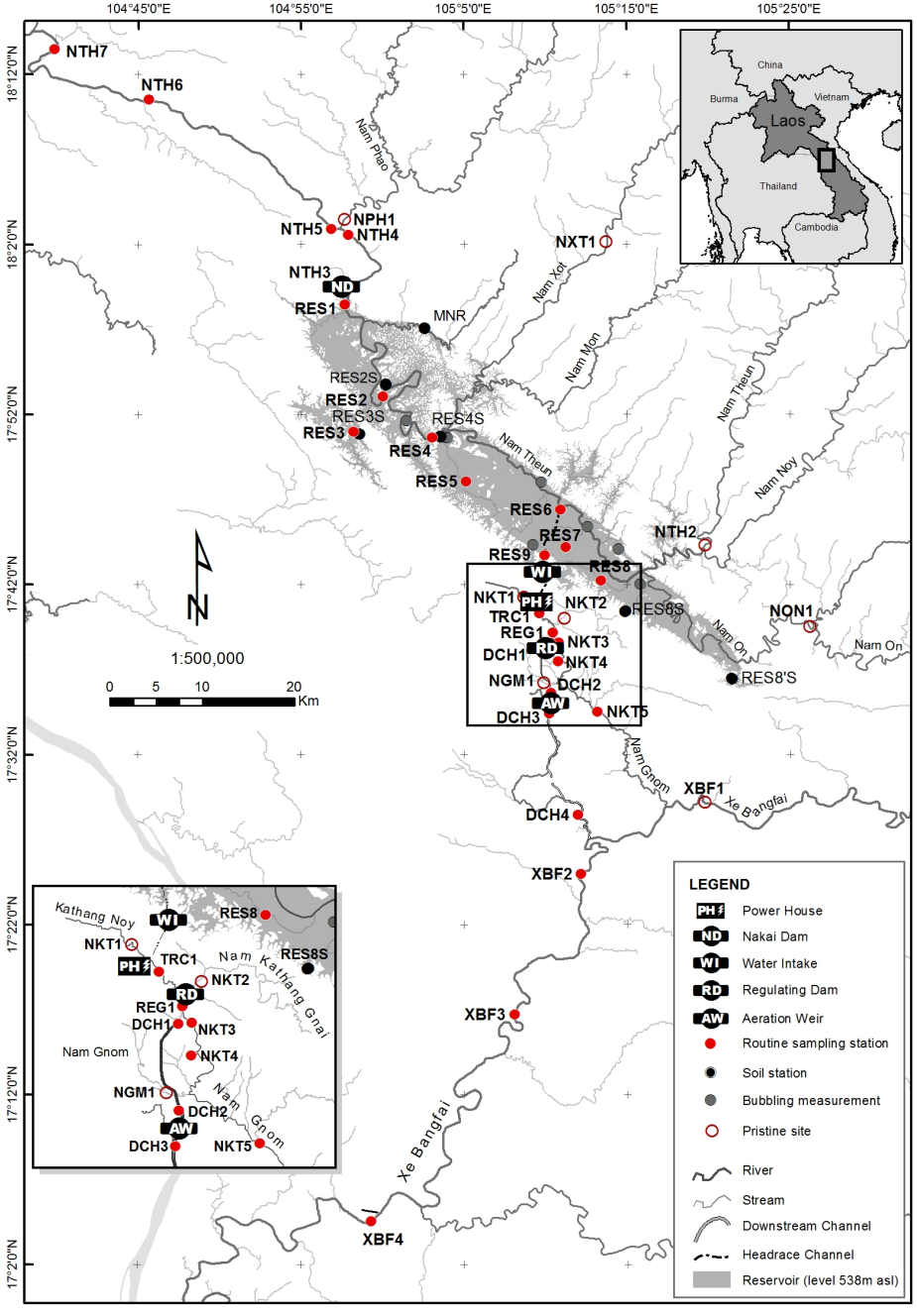

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Figure 2 : Median and interquartile range (boxes), average (+), and full range of values (whiskers) of particulate organic carbon (POC), dissolved organic carbon (DOC), total inorganic carbon (TIC) and CO2 concentrations in four pristine river of the 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.

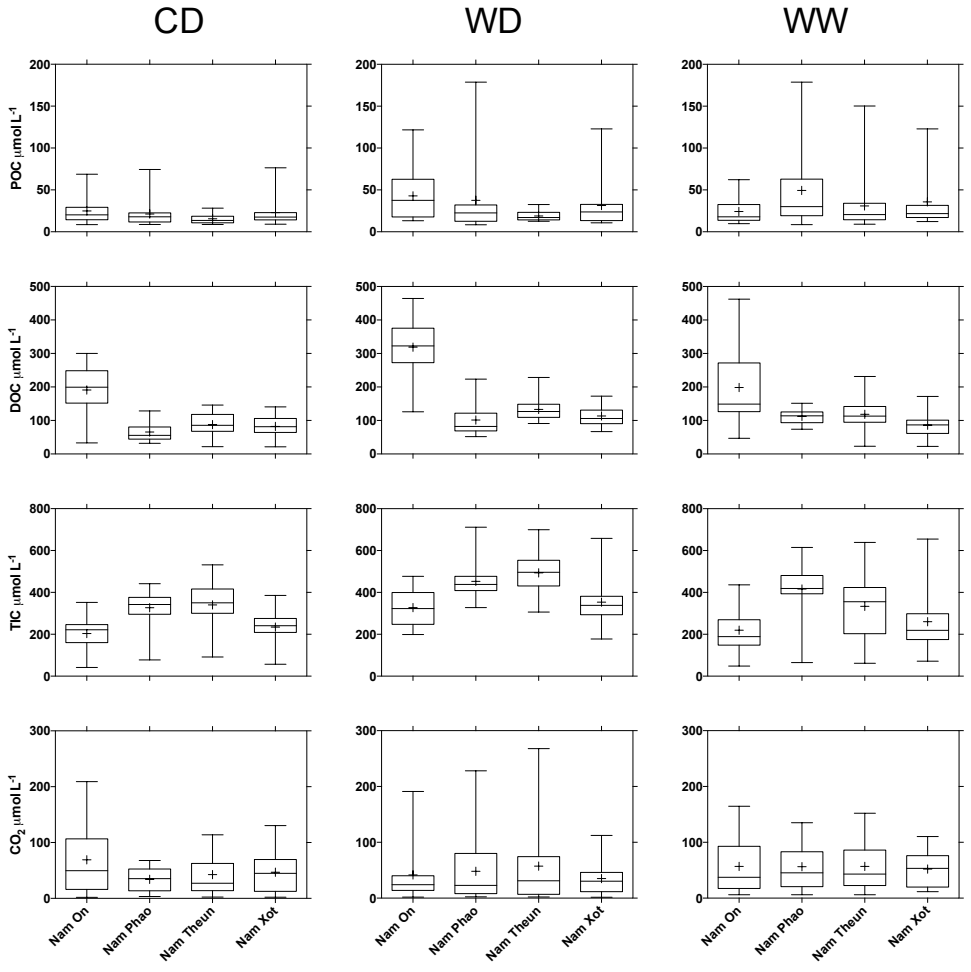

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Figure 3: Total carbon inputs in form of particulate organic carbon (POC), dissolved organic carbon (DOC) and total inorganic carbon (TIC) from the Nam Theun watershed to the Nam Theun 2 Reservoir for four distinct years after reservoir impoundment.

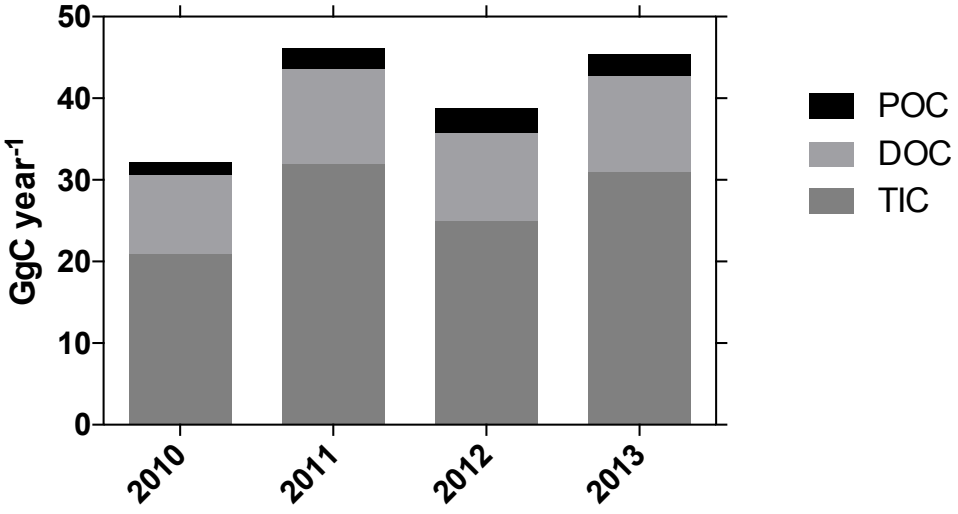

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Figure 4: Temperature (grey solid circle) and oxygen (black solid circle), DOC (open square), POC (solid square) and CO_2(triangle) concentrations in the Nam Theun 2 Reservoir water column during the cool dry, warm dry and warm wet seasons in 2011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

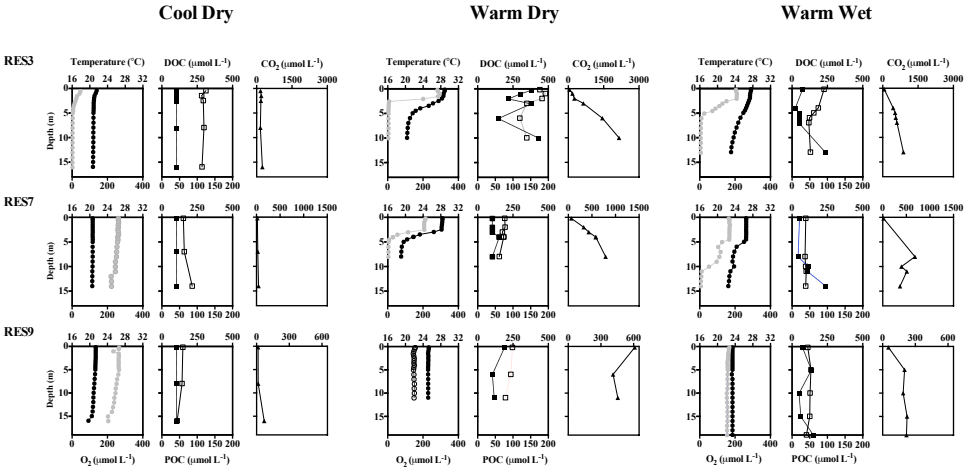

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Figure 5: (a) Monthly average CO_2 concentrations at the stations RES1-8 (a) and at the station RES9 (b), average diffusive fluxes at the stations RES1-8 (c) and at the station RES9 (d) and total monthly (e) and yearly (f) CO_2 emissions by diffusive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

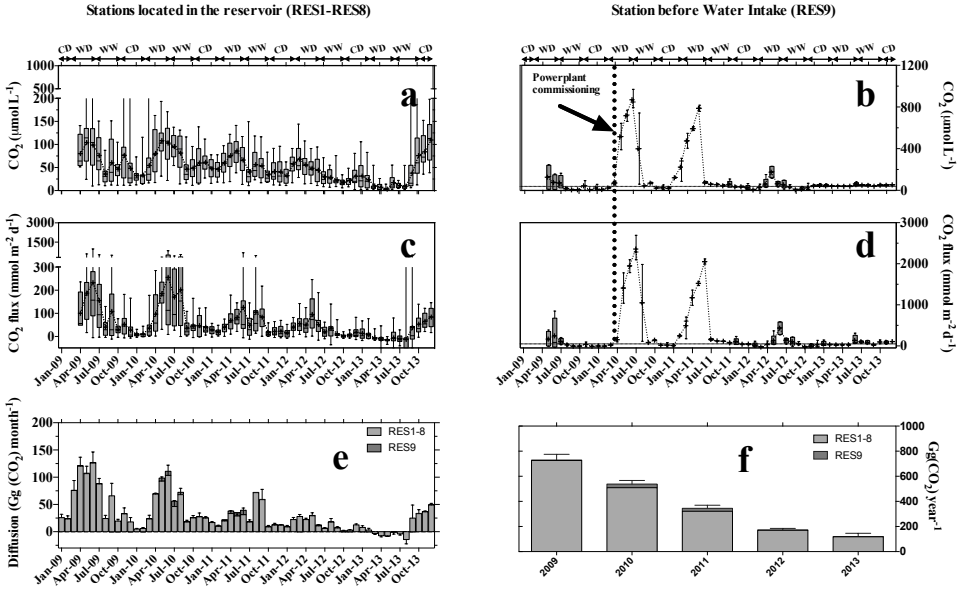

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Figure 6: Diffusive fluxes and degassing below the powerhouse and the Nakai Dam on a monthly (a) and yearly basis (b) at the Nam Theun 2 Reservoir (Lao PDR). Note that degassing below ND includes spillway release (main contributor to 2009 and 2011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

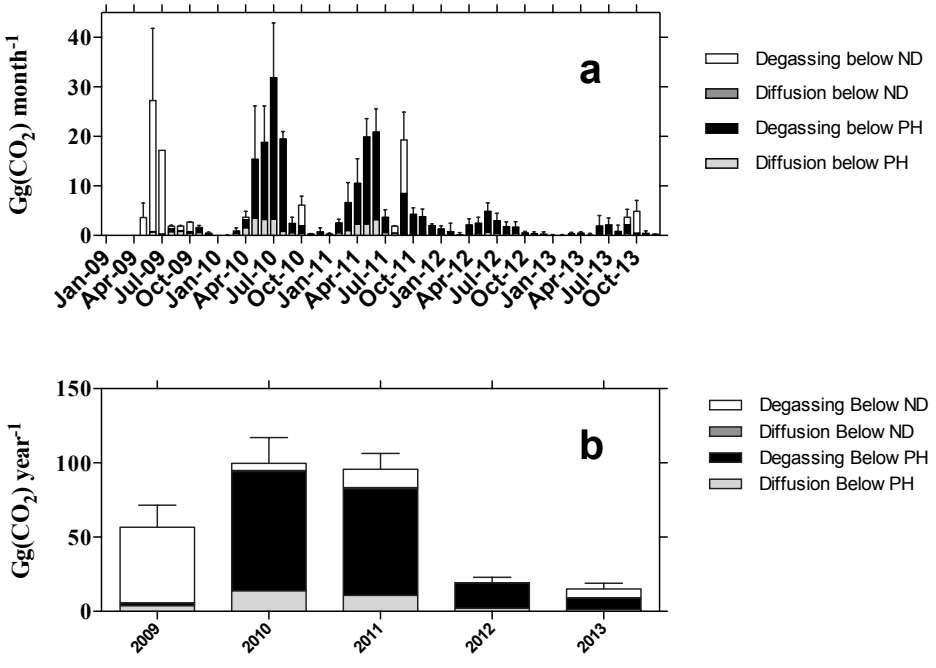

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Figure 7: Monthly emissions from the drawdown area and variation of the area of the drawdown area of the Nam Theun 2 Reservoir (Lao PDR)

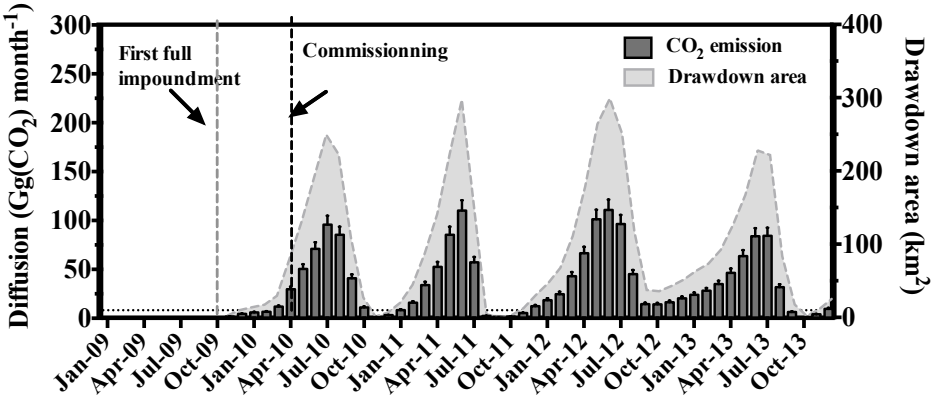

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Figure 8: Monthly (a) and yearly (b) average of the total emissions from the Nam Theun 2 Reservoir by diffusion at the reservoir surface, diffusion from the drawdown area, ebullition, degassing and diffusion from the Nam Theun River and artificial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