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 (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.

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

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

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

123 2.2 Sampling strategy

124 The CO_2 and O_2 concentrations in water and the water temperature were determined in
125 surface waters of six pristine rivers and three rivers under the influence of the reservoir (10
126 stations) and in the artificial channel (5 stations) whereas it was done along vertical profiles in
127 the reservoir (9 stations) and the regulation pond (1 station) (Figure 1). At all sites located
128 downstream of the powerhouse, sampling was done weekly (from March 2010 to December
129 2013) whereas it was done fortnightly in incoming pristine rivers and in the reservoir (from
130 May 2009 to December 2013). The stations RES1-RES3 flooded dense forest, the stations
131 RES4-RES6 flooded degraded forest, the station RES7 flood swamps and the station RES8
132 flooded a rice field area (Descloux et al., 2011;Guérin et al., 2016). The station RES9 is
133 located at the water intake, an area of continuous vertical mixing of the water column, where
134 CH_4 emissions are enhanced (Guérin et al., 2016). Degassing of CO_2 was calculated below
135 the Nakai Dam, just below the turbines at TRC1, below the regulating dam (RD on Figure 1)
136 and at the aeration weir (AW on Figure 1). Bubbling of CO_2 was determined during five field
137 campaigns covering different seasons and sites in 2009, 2010 and 2011, and during a weekly
138 monitoring from March 2012 to August 2013 at seven stations. In the drawdown area, soil
139 description was conducted in June 2010 at six sites and CO_2 emissions were repeatedly
140 measured at 21 plots over those sites in June 2010, 2011 and 2013.

141 2.3 In situ measurements and water analysis

142 Vertical profiles of O_2, pH and temperature were measured in situ at all sampling stations
143 with a multi-parameter probe Quanta® (Hydrolab, Austin, Texas) since January 2009. In the
144 reservoir, the vertical resolution was 0.5 m down to 5 m and and 1 m deeper. Surface and
145 deep-water samples for CO_2, dissolved organic carbon (DOC), particulate organic carbon
146 (POC) and dissolved inorganic carbon (DIC) concentrations were taken with a surface water
147 sampler (Abril et al., 2007) and a UWITEC™ sampling bottle, respectively. Water samples
148 for CO_2 determination were stored in serum glass vials, capped with butyl stoppers, sealed
149 with aluminium crimps and preserved (Guérin and Abril, 2007). CO_2 concentrations were
150 determined by the headspace technique and using the solubility coefficient of Weiss (1974) as
151 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

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

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,

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

281 Over the monitoring period at the stations RES1-RES8, the average CO_2 concentration in the
282 water column was 389±9 μmol L^{-1} and ranged from 0.3 to 4770 μmol L^{-1} (n=3698). It
283 decreased from 544±24 μmol L^{-1} in 2010 to 154±9 μmol L^{-1} in 2013. During the WD and
284 WW seasons, CO_2 concentrations increased with water depth and often showed a maximum
285 gradient at or just below the thermocline (Figure 4). For the years 2010 to 2013, the average
286 CO_2 concentrations in the water column during the WD and WW seasons were always 50%
287 higher than in the CD season (Figure 4). DOC concentrations averaged 181±1 μmol L^{-1} and
288 ranged from 12.5 to 569 μmol L^{-1} (n=3068). For the years 2010, 2011 and 2012 we observed
289 a significant decrease of DOC in the water column from year to year with average DOC
290 concentrations 208±3 μmol L^{-1} in 2010, 190±3 μmol L^{-1} in 2011 and 177±2 μmol L^{-1} in 2012.
291 In 2013, the DOC was not significantly lower than in 2012 (175±2 μmol L^{-1}). From 2010 to
292 2013, DOC concentrations were about 25% higher in the WD and WW seasons than in the
293 CD season. Whatever the year, the average epilimnic DOC concentration was 30% higher
294 than in hypolimnic water. POC concentration was 63±2 μmol L^{-1} (n = 2488). POC in
295 hypolimnic waters (92±3 μmol L^{-1}) was almost twice higher than in the epilimnion (45±2
296 μmol L^{-1}) ($p < 0.0001$, t-test). The POC in the epilimnion decreased significantly from 41±4
297 μmol L^{-1} in 2010 to 23±2 μmol L^{-1} in 2013 in the epilimnion ($p < 0.0001$). POC in
298 hypolimnic waters did not show any consistent trend with yearly average values being 87±6
299 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
300 μmol L^{-1} in 2013. No clear seasonal variation was observed.

301 At the station RES9 where the presence of the water intake enhances vertical mixing of the
302 water column leading to the transport of bottom water to the surface, the water column is not
303 thermally stratified and always oxygenated from the surface to the bottom after the reservoir
304 was commissioned in April 2010 (Guérin et al., 2016) (Figure 4). Since commissioning, O_2
305 saturation was 60±2 % over the water column. The water column was significantly more
306 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.

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.

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).

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).

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.

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}.

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,

487 the higher concentrations were observed during the warm seasons due to long residence tie of
488 water and warmer conditions enhancing CO_2 build-up (Abril et al., 2005;Kemenes et al.,
489 2011;Chanudet et al., 2011) whereas the lowest were found after reservoir overturn when the
490 water outgassed (Chanudet et al., 2011). A significant shift in the carbon biogeochemical
491 cycling occurred in the reservoir in 2013 with the reservoir water surface becoming of CO_2
492 sink during the WD season and the beginning of the WW season (from March to August).
493 Although no major change was observed in nutrient concentrations, the number of
494 phytoplanktonic cell was 50% higher in 2013 than 2012 (Unpublished, M Cottet personal
495 com.) indicating that primary production was significantly enhanced in 2013. Despite the fact
496 that the reservoir was a sink for the six months when CO_2 emissions are usually the highest of
497 the year, annual CO_2 emissions at the surface of the reservoir were only 50% lower in 2013
498 than in 2012. In 2013, CO_2 was mainly emitted in the CD after the period of high biological
499 productivity suggesting that the degradation of autochthonous OM fuels CO_2 emissions.

500 The maximum concentration and the highest CO_2 stock in the water column highly depend on
501 the age of the reservoir. In the NT2R, average CO_2 concentration was three times higher in
502 2010 than in 2013 and the maximum concentrations in 2010 was almost two times higher than
503 in 2013 (4771 μmol L^{-1} in 2010 vs. 2649 μmol L^{-1} in 2013). Those high concentrations are
504 slightly lower than the maximum concentration measured in the hypolimnion of the Petit Saut
505 Reservoir less than a year after it was flooded (Galy-Lacaux et al., 1997a;Abril et al., 2005).
506 Disregarding these high concentrations observed in the hypolimnion of the reservoir at the
507 end of the WD season and beginning of the WW season in 2009 and 2010, the CO_2
508 concentration in the NT2R are in the same range as concentrations in other older reservoirs in
509 the tropics or the subtropics (Abril et al., 2005;Guérin et al., 2006;Chanudet et al.,
510 2011;Kemenes et al., 2011). This decrease during the first four years after impoundment is
511 very consistent with the decrease of the CO_2 concentration with the reservoir age as already
512 observed at the Petit Saut Reservoir (Abril et al., 2005), at the Eastmain I Reservoir (Teodoru
513 et al., 2012) or over multi-sites study (Barros et al., 2011).

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

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

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

540 Downstream of the reservoir in the Nam Theun River or the artificial channel, CO_2
541 concentrations follow the same seasonality as in the reservoir. Concentrations peak in June-
542 July at the transition between the WD and the WW season, and reach their minima in the CD
543 season. Downstream of the Nakai Dam, the concentrations are twice lower than downstream
544 of the powerhouse since mostly epilimnic water from the RES1 station is transferred
545 downstream of the dam. Within less than 10 km further downstream, concentrations are not
546 significantly different than in pristine rivers of the watershed. Downstream of the
547 powerhouse, CO_2 concentrations in 2010 were in the same order of magnitude as in 10-20
548 years-old reservoirs in South America flooding tropical forest (Abril et al., 2005;Guérin et al.,
549 2006;Kemenes et al., 2011) whereas four years after impoundment CO_2 concentrations were
550 two times lower than in 20-30 years-old reservoirs in Lao PDR (Chanudet et al., 2011). We

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.

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

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

630 This is the first comprehensive quantification of CO_2 emissions from a reservoir where all
631 known CO_2 pathways to the atmosphere were taken into account at one of the best spatial and
632 temporal resolution reported in the literature. We showed that downstream emissions and
633 emissions around the water intake are not negligible (~10% overall) and that the overlooked
634 drawdown area in CO_2 studies could be the main emission pathway of CO_2 to the atmosphere.
635 Overall, this study highlights that global estimate of CO_2 emissions from reservoir are
636 underestimated so far since relevant pathways like drawdown emissions in flat/shallow
637 reservoirs with large water level variations and downstream emissions in thermally stratified
638 reservoirs are missing in most site-specific studies used for extrapolations (Deemer et al.,
639 2016;Barros et al., 2011).

640 ### 4.3 Source of organic matter fuelling the reservoir CO_2 emissions

641 In tropical reservoirs, the decrease of the CO_2 concentration in the water column and
642 subsequent emissions with the age of the reservoir (Figure 8b) is supposed to result from the
643 decrease of the aerobic and anaerobic mineralisation rate due to the exhaustion of labile OM
644 from the pool of soil and vegetation that was flooded during impoundment (Abril et al.,
645 2005;Guérin et al., 2008). In boreal reservoirs, the decrease of benthic CO_2 production is

sharp and after 3-5 years, most of the CO_2 production appears to be pelagic and is supposed not to result from the flooded organic matter (Teodoru et al., 2011;Brothers et al., 2012). The total CO_2 emissions were nine and three times higher than the carbon inputs from the watershed to the NT2R in 2010 (32 GgC yr^{-1}) and 2013 (45 GgC yr^{-1}), respectively (Figure 3 and Table 3). It has to be noted that interannual variations of carbon inputs to the NT2R (Figure 3) are not correlated with the regular decrease of total CO_2 emissions from year to year (Figure 8b). It is therefore unlikely that most of CO_2 emissions result from the mineralization of allochthonous OM but rather from the contribution of the flooded carbon pool (soil and vegetation) which amount is decreasing with time. This is consistent with the fact that at Petit Saut, even 10 years after flooding, the majority of the OM in the water column has a terrestrial origin (De Junet et al., 2009). 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). We show here, as it was done at Petit Saut (Guérin et al., 2008;Abril et al., 2005), that external sources of carbon are not sufficient to fuel the CO_2 emissions from the NT2R and we attribute the decrease of emissions with time to the exhaustion of the most labile fraction of the flooded pool of OM which might be the main source of reactive carbon in the reservoir.

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

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

713 ## 5 Conclusions

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

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

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

729 We found that gross CO_2 emissions from the drawdown area represented 40- 75% of the total
730 emissions from the NT2R and they occur within a few months during low water level seasons.
731 The soil organic matter from these areas undergoes anaerobic degradation and fuels the
732 reservoir water column in CO_2 during the wet season. In the dry season, the soil loss CO_2
733 directly to the atmosphere while undergoing both aerobic and anaerobic mineralisation
734 depending on the soil moisture content. We hypothesize that both (1) the potential
735 development of bacteria and micro-phytobenthos at the surface of these soils and (2) the
736 oxic/anoxic variations contribute to the mineralisation of stabilized SOM leading to a
737 sustained high soil respiration even after the pristine vegetation decayed. This overlooked
738 pathway in terms of gross emissions would require an in-depth evaluation for the soil OM and
739 vegetation dynamics and long-term monitoring of emissions to evaluate the real contribution
740 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		

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.

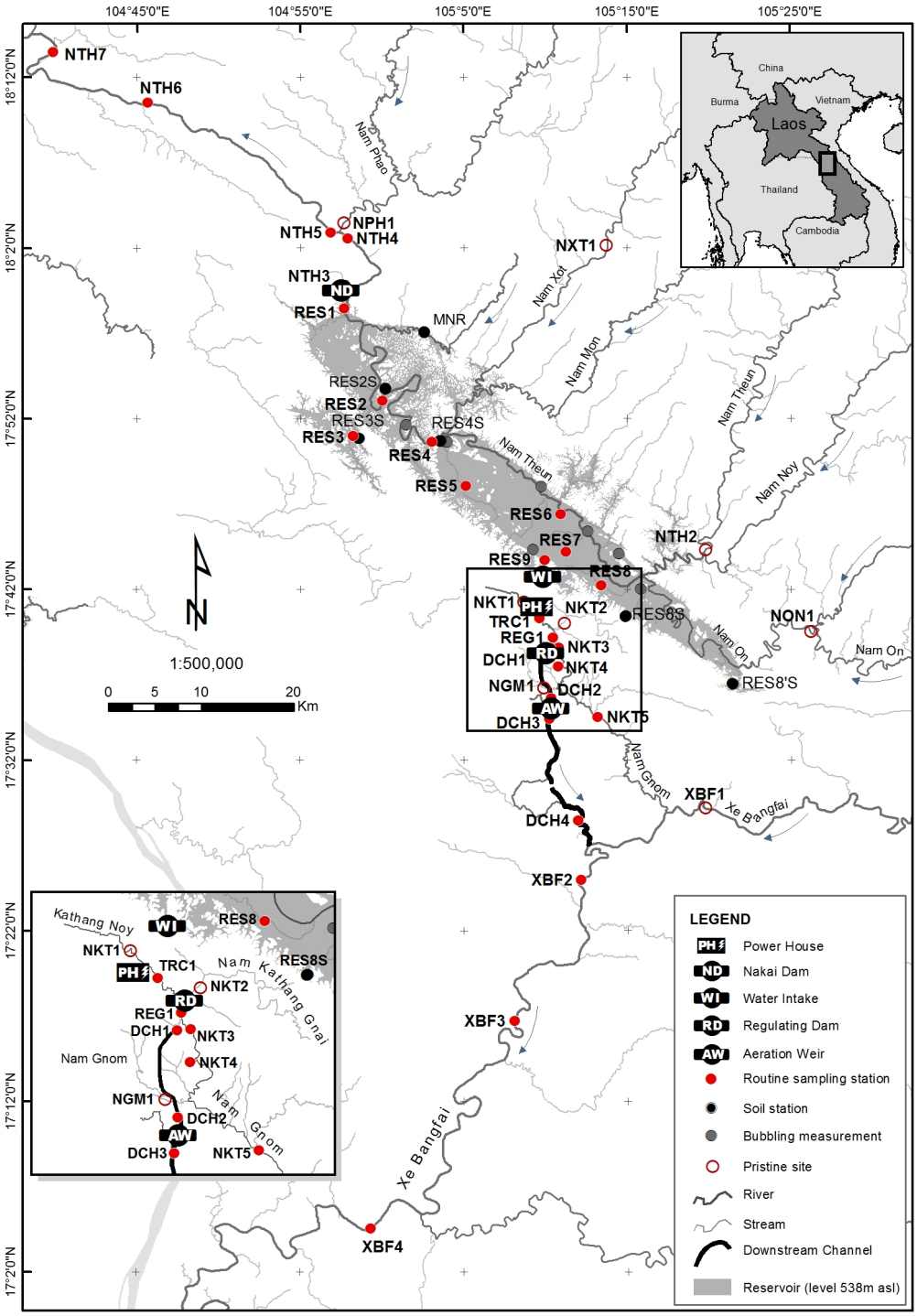

Figure 2 : Median and interquartile range (boxes), average (+), and full range of values (whiskers) of particulate organic carbon (POC), dissolved organic carbon (DOC), total inorganic carbon (TIC) and CO2 concentrations in four pristine river of the Nam Theun watershed during three distinct seasons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

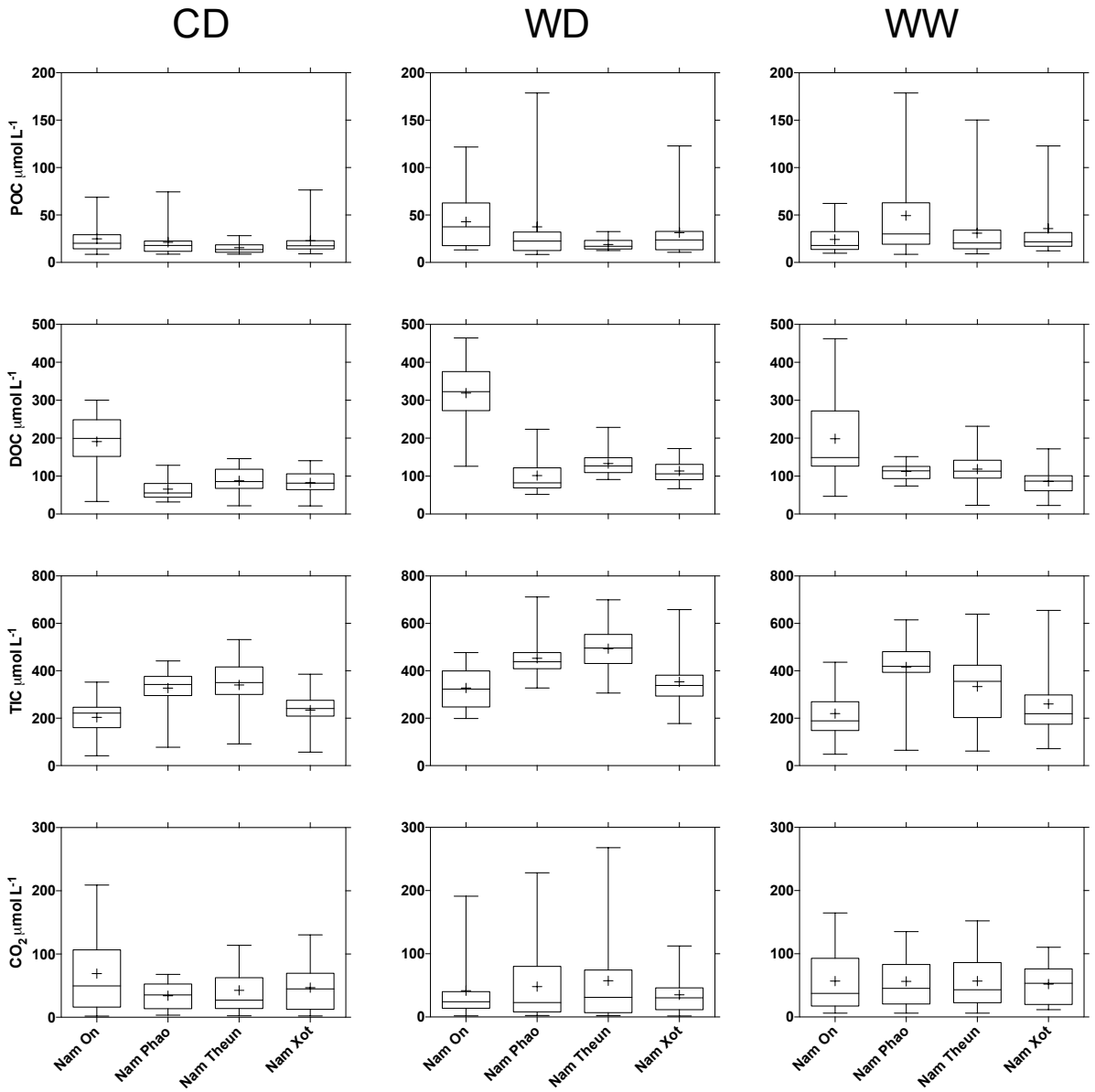

Figure 3: Total carbon inputs in form of particulate organic carbon (POC), dissolved organic carbon (DOC) and total inorganic carbon (TIC) from the Nam Theun watershed to the Nam Theun 2 Reservoir for four distinct years after reservoir impoundment.

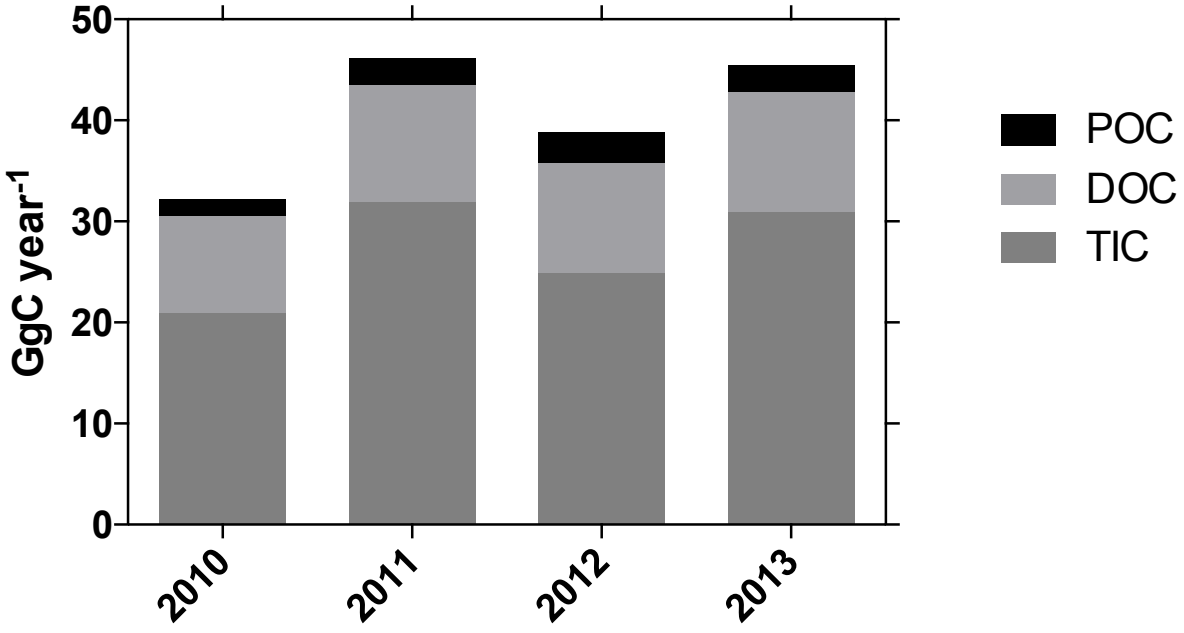

Figure 4: Temperature (grey solid circle) and oxygen (black solid circle), DOC (open square), POC (solid square) and CO_2(triangle) concentrations in the Nam Theun 2 Reservoir water column during the cool dry, warm dry and warm wet seasons in 2011 at three stations (RES3, RES7 and RES9).

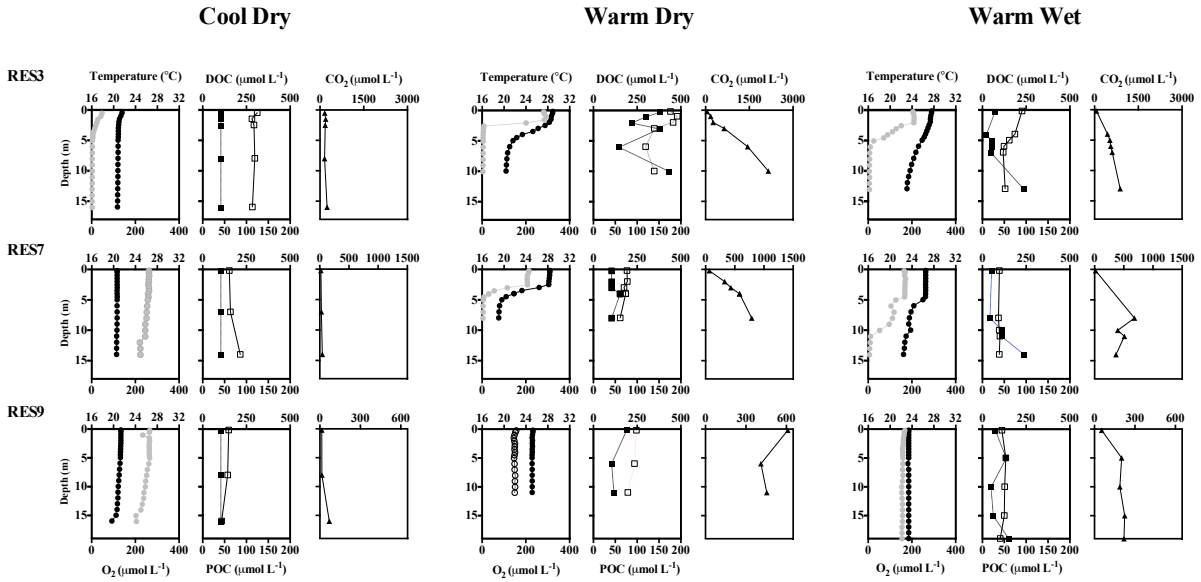

Figure 5: Monthly average CO_2 concentrations at the stations RES1-8 (a) and at the station RES9 (b), average diffusive fluxes at the stations RES1-8 (c) and at the station RES9 (d) and total monthly (e) and yearly (f) CO_2 emissions by diffusive fluxes from the Nam Theun 2 Reservoir (Lao PDR)

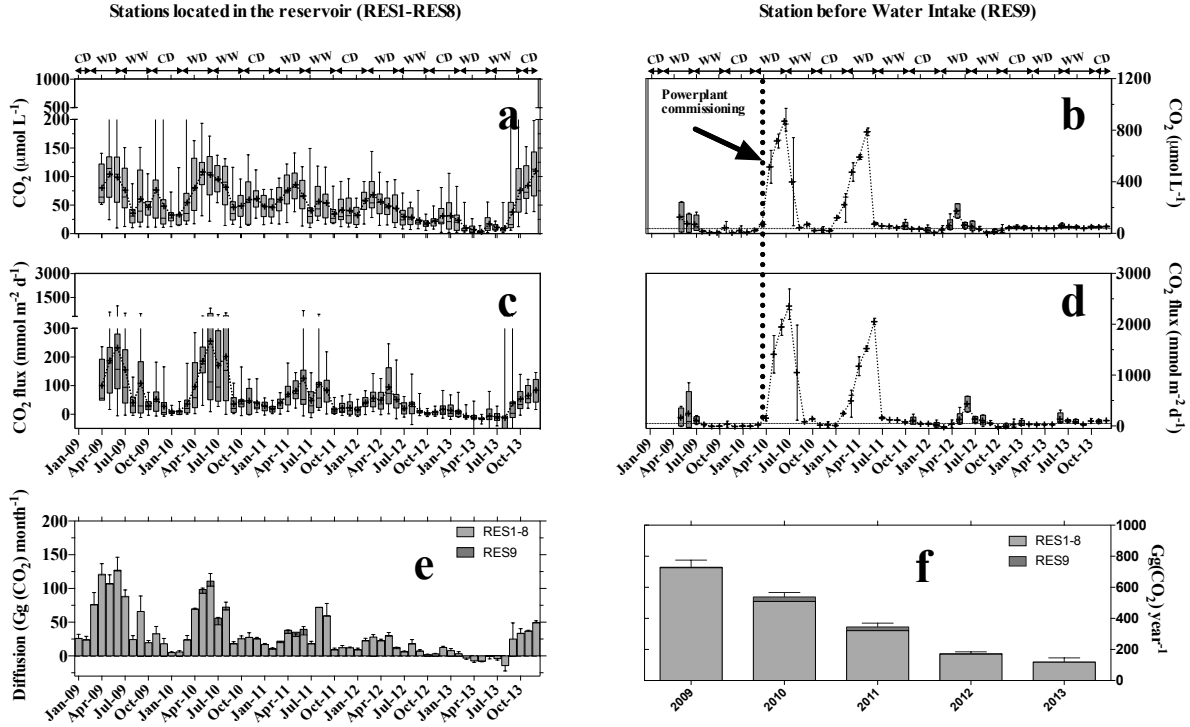

Figure 6: Diffusive fluxes and degassing below the powerhouse and the Nakai Dam on a monthly (a) and yearly basis (b) at the Nam Theun 2 Reservoir (Lao PDR). Note that degassing below ND includes spillway release (main contributor to 2009 and 2011 emissions below ND). Degassing below the powerhouse includes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

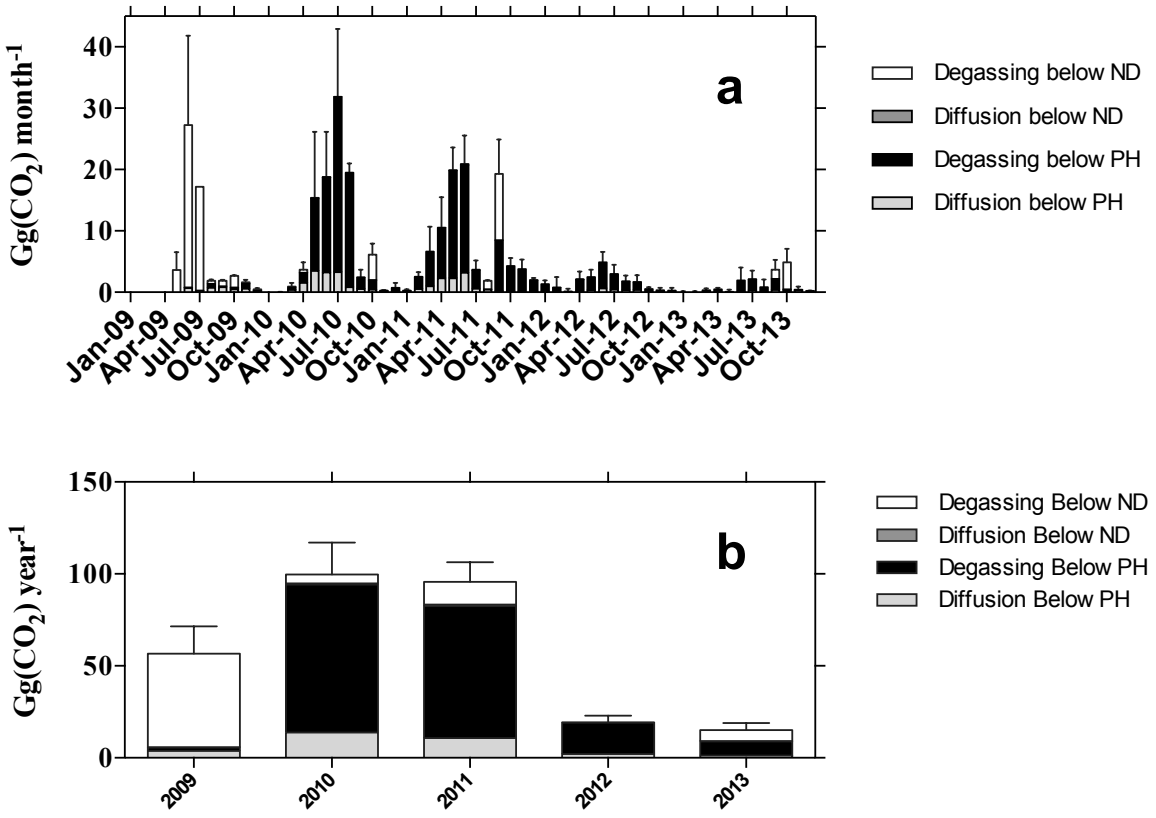

Figure 7: Monthly emissions from the drawdown area and variation of the area of the drawdown area of the Nam Theun 2 Reservoir (Lao PDR)

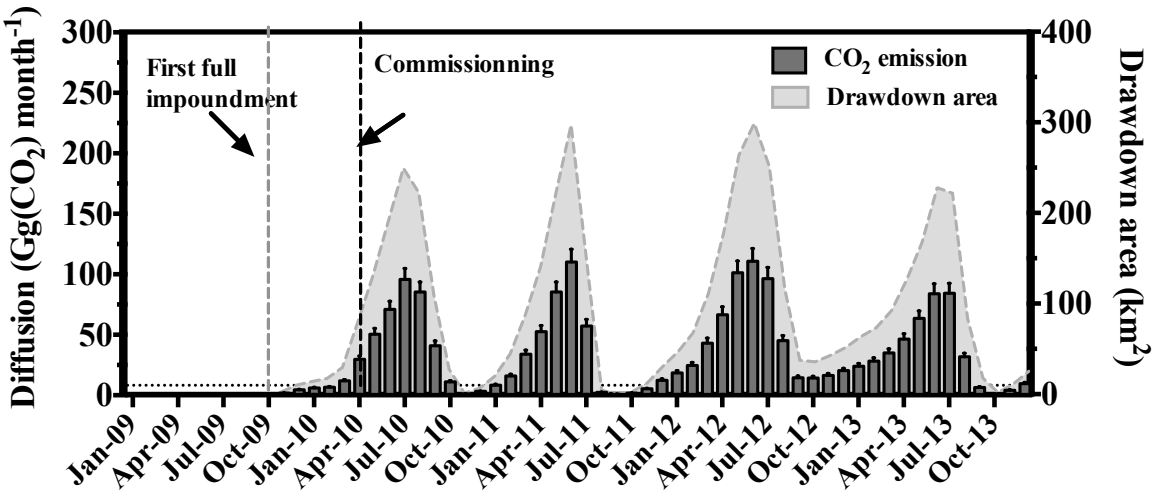

Figure 8: Monthly (a) and yearly (b) average of the total emissions from the Nam Theun 2 Reservoir by diffusion at the reservoir surface, diffusion from the drawdown area, ebullition, degassing and diffusion from the Nam Theun River and artificial channel at the Nam Theun 2 Reservoir (Lao PDR). On panel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