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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 CO₂ to the atmosphere. CO₂ 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 CO₂ 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 the end of 2013. We tested the hypothesis that soils from the drawdown area would be a significant contributor to the total CO₂ emissions.

Total inorganic carbon, dissolved and particulate organic carbon and CO₂ 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. CO₂ bubbling was estimated during five field campaigns between 2009 and 2011 and on a weekly monitoring, covering water depths ranging from 0.4 to 16 m 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 CO₂ emissions from the drawdown area. On this basis, we calculated total CO₂ 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 carbon (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 CO₂ emissions from the drawdown zone are almost constant throughout the years, the large interannual variations result from the significant decrease in 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 organic matter 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 (CO₂) emissions from inland waters were recently revisited and it appears that emissions from freshwater reservoirs contribute significantly despite the disproportionately small surface area of these systems (Barros et al., 2011; Raymond et al., 2013; Deemer et al., 2016). The CO₂ 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 mineralization of the carbon stock, emissions decrease progressively with reservoir ageing (Abril et al., 2005; Barros et al., 2011). CO₂ 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 significantly vary 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, the Three Gorges and Nam Theun 2 reservoirs). Recently, the importance of the drawdown emissions was pointed out as a significant source of CH₄ in the Three Gorges Dam in China (Chen et al., 2009, 2011; Yang et al., 2012) and a very minor source at Nam Theun 2 Reservoir (NT2R; Serça et al., 2016). CO₂ 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 CO₂ emissions from those soils seasonally flooded and exposed to

air was never tested in unmanaged drawdown areas representative of tropical reservoirs with large water-level variations. In the present study, we measured CO₂, 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 CO₂ 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 in emissions by all of the above-listed pathways and their contribution to total gross CO₂ emissions will be discussed.

2 Material and methods

2.1 Study site

The NT2R is located in the Lao People's Democratic Republic (Lao PDR), it was impounded in April 2008 and was commissioned in April 2010. It floods 489 km² 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 of 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) and Guérin et al. (2016) is under the influence of a monsoon subtropical climate with three main seasons: the cold dry season (CD, from mid-October to mid-February), the warm dry season (WD, from mid-February to mid-June) and the warm wet season (WW, from mid-June to mid-October). Owing to the large seasonal variations in the river discharges in the region, the reservoir area ranged seasonally between 489 km² in the WW season and 170 km² in the WD season during the course of the study. Conversely, the surface of the drawdown area reached its maximum (320 km²) 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 $\sim 270 \text{ m}^3 \text{ s}^{-1}$, whereas the driest year was 2012 with a discharge of $230 \text{ m}^3 \text{ s}^{-1}$. In 2011, the reservoir had the largest water-level variation with the largest surface area of the monitoring in the wet season (491 km²) and the smallest of the monitoring in the WD season (168 km²). The NT2R is a trans-basin reservoir with two downstream sections: one be-

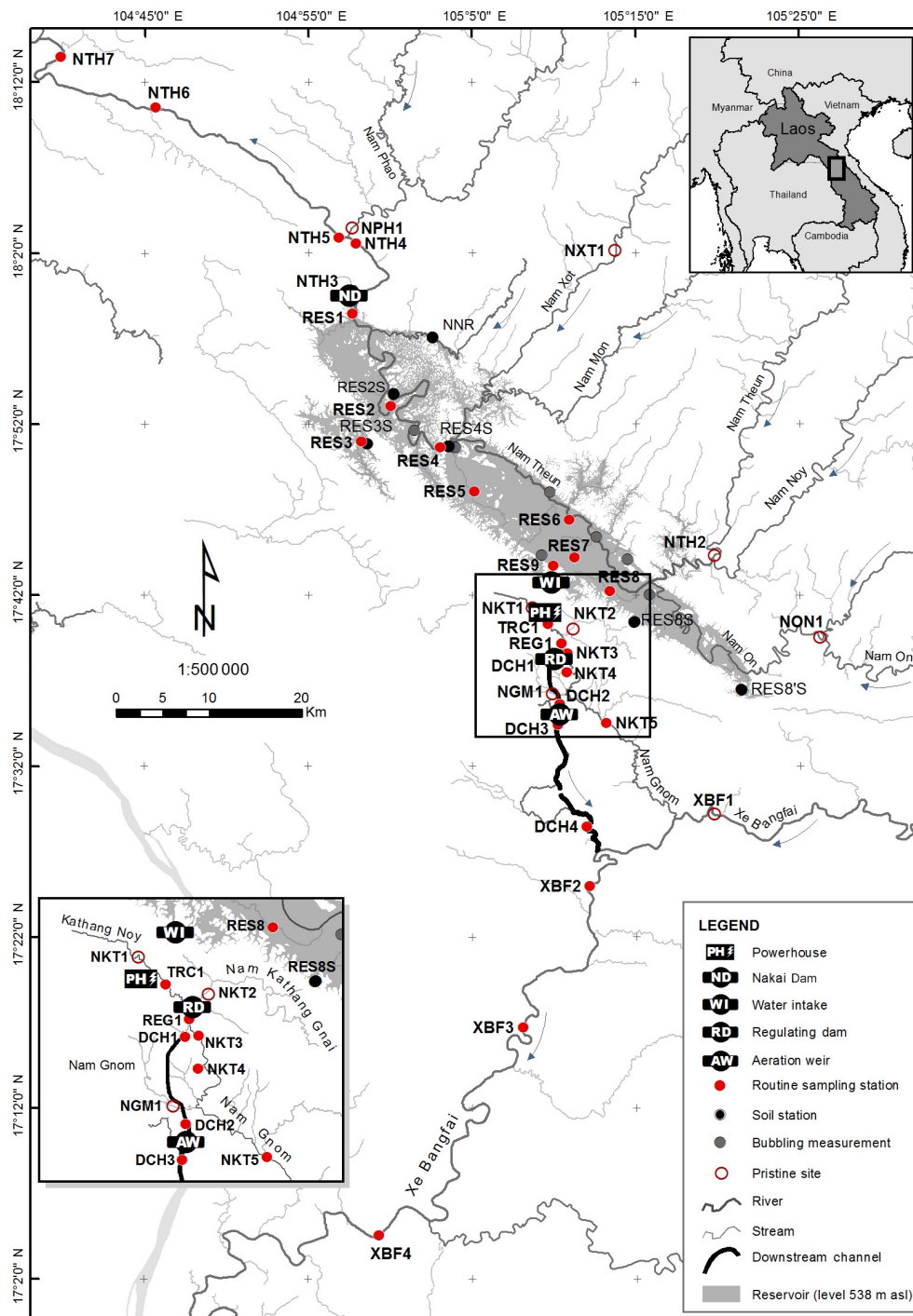


Figure 1. Map of the Nam Theun 2 monitoring network. The station names are defined by numbers and an abbreviated name as follow: RES standing for reservoir, NTH for Nam Theun River, NON for Nam On River, NXT for Nam Xot, NPH1 for Nam Phao River, TRC for tail race channel, REG for regulation pond, DCH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

low the powerhouse and one below the Nakai Dam (Fig. 1). Except for during the occasional use of the spillways, only $2\text{ m}^3\text{ s}^{-1}$ of water are discharged downstream of the Nakai Dam in the Nam Theun River and around $240\text{ m}^3\text{ s}^{-1}$ are re-

leased to the powerhouse, the regulating pond and finally the artificial downstream channel before water reaches the Xe Bangfai River (Fig. 1).

2.2 Sampling strategy

The CO₂ and O₂ 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; Fig. 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 CH₄ emissions are enhanced (Guérin et al., 2016). Degassing of CO₂ was calculated below the Nakai Dam, just below the turbines at TRC1, below the regulating dam (RD in Fig. 1) and at the aeration weir (AW in Fig. 1). Bubbling of CO₂ 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 CO₂ 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 O₂, 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 1 m deeper. Surface and deep-water samples for CO₂, 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 CO₂ determination were stored in serum glass vials, capped with butyl stoppers, sealed with aluminium crimps and preserved (Guérin and Abril, 2007). CO₂ concentrations were determined by the headspace technique and using the solubility coefficient of Weiss (1974) as in Guérin et al. (2006). The CO₂ partial pressure in the 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. The detection limit was < 1 ppmv in the 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. Fil-

tered (0.45 µm, Nylon) and unfiltered samples were analysed for TIC and total organic carbon (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 the uncertainty was 2.0 µmol L⁻¹ in TOC and DOC and 2.8 µmol L⁻¹ in POC.

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

Carbon inputs were calculated on a monthly basis using monthly averages of the river discharge of the four main tributaries of the NT2R. The Nam Theun River contributed 32 % (27 m³ s⁻¹) of the total discharge, while Nam Xot (22 m³ s⁻¹), Nam On (19 m³ s⁻¹) and Nam Noy (25 m³ 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 CO₂ 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 CO₂ 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 CO₂ 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 CH₄ 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 km² (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 (Fig. 1), were computed using the CO₂ concentration upstream and downstream of these civil structures and the water discharge as in Deshmukh et al. (2016) for CH₄. 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).

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
NNR	NNR upland	0.11	1.47	13.69 ± 1.73	4.33	planosol	sandy	micaceous quartzose
	NNR interm. down	0.10	1.32	13.55 ± 1.84		endogleyic planosol		
	NNR 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 sandstone
	RES2 interm.	0.20	2.30	11.25 ± 0.50		“stagnic” ferralsol		
	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 sandstone
	RES4 interm. up	0.13	1.92	14.66 ± 1.58		stagnic acrisol		
	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		

2.6 CO₂ bubbling

Bubbling of CO₂ 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 16 m 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 N₂-pre-flushed 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 CO₂ 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 CO₂ emissions. Soil description was carried out in June 2010 at six sites and soils from the station RES4S plot were characterized in detail in June 2013

(Fig. 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 two to four soils profiles from the pristine soils on top (“upland” samples) to the shoreline of the reservoir (“shoreline” samples). One or two other soil 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 1 m, but only 0–20 cm depth samples were considered in this study. Information on horizon depth, soil texture and structure (e.g. compactness, porosity), colour (Munsell chart for soil colour), soil fauna activity, and pedological features (e.g. redoximorphic features, concretions) were provided through soil descriptions in the field. Samples for C, N and pH were selected following the horizon 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 were 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.

Table 2. Temperature (°C), relative humidity (%) and CO₂ fluxes (mmol m⁻² d⁻¹) from the soils of the drawdown area of the Nam Theun 2 Reservoir (Lao PDR).

Site	2010			2011			2013		
	Hum.	Temp.	CO ₂ flux	Hum.	Temp.	CO ₂ flux	Hum.	Temp.	CO ₂ flux
NNR upland	17.5	25.7	265 ± 37	18.3	24.4	328 ± 43			
NNR interm. up				26.9	27.5	669 ± 56			
NNR interm. down	19.6	32.3	201 ± 19	23.7	29	251 ± 99			
NNR 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			
RES3S shoreline	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

At the six 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 CO₂ fluxes were gathered, mostly in duplicates (from 1 to 4 replicates; Table 2). CO₂ emissions were measured during three field campaigns in 2010, 2011 and 2013 using a stainless steel chamber (volume 12 L, 0.08 m²) described in Serça et al. (1994, 2016). At each site, two chambers were deployed in parallel and the collars were installed at least 1 h prior to measurement. Air samples were taken and stored with the same methodology as for bubbling samples every 15 min in each chamber before subsequent GC analysis. It has to be noted that soil studies and measurement of fluxes were restricted for safety reasons due to the high density of unexploded ordinances from the 60s and 70s in that area.

3 Results

3.1 Temperature, oxygen, pH, and 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 CO₂ concentrations (59 ± 6 μmol L⁻¹, $n = 107$) and the lowest TIC concentration (237 ± 11 μmol L⁻¹, $n = 107$; Fig. 2). The Nam Phao and the Nam Theun rivers are not significantly different in terms of POC, DOC, TIC and CO₂ concentrations (Fig. 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 2 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, $n = 97$; Fig. 2). CO₂ 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

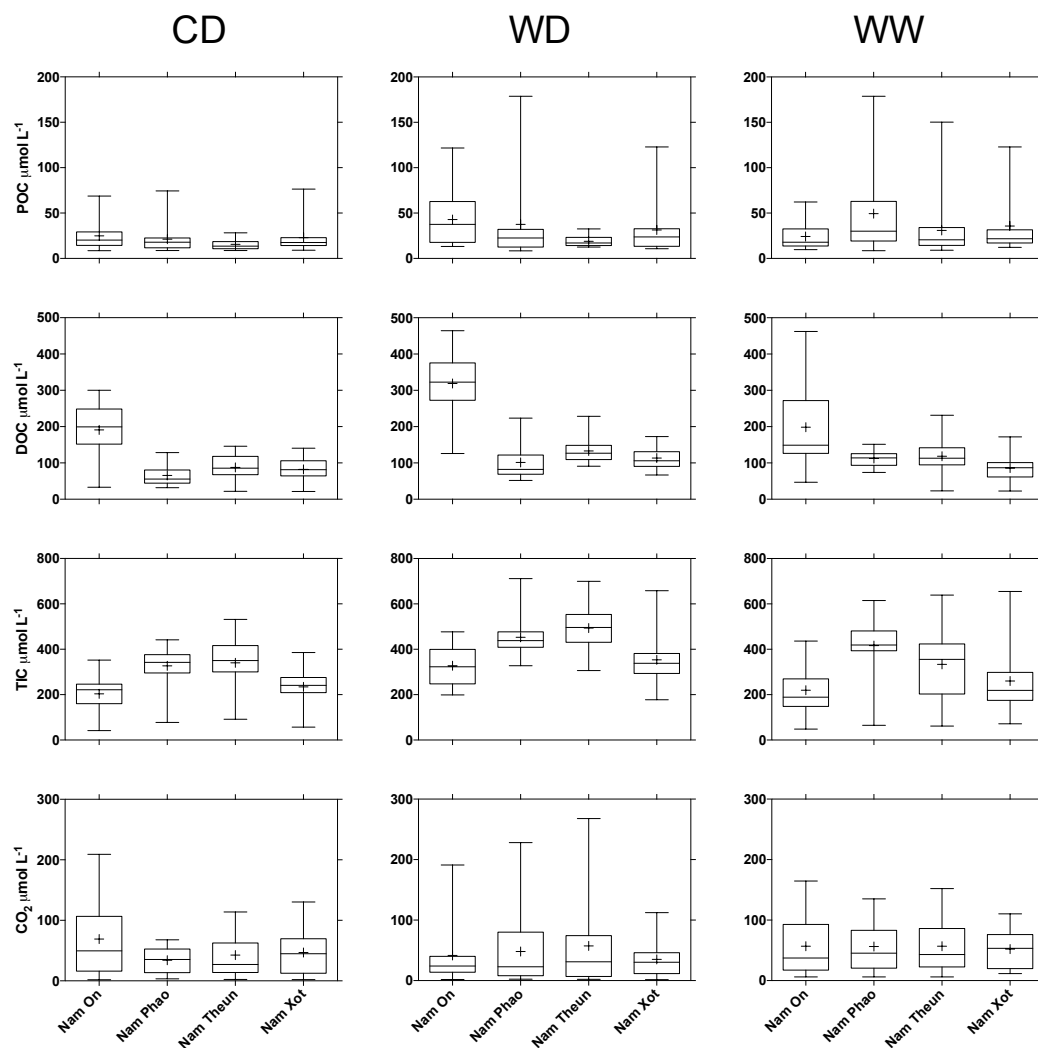


Figure 2. Median and interquartile ranges (boxes), average (+), and full range of values (whiskers) of particulate organic carbon (POC), dissolved organic carbon (DOC), total inorganic carbon (TIC) and CO₂ concentrations in four pristine rivers of the Nam Theun watershed during three distinct seasons: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

15 % of TIC whereas it was almost 25 % in the Nam On. The Nam Xot River had amongst the lowest DOC ($90 \pm 3 \mu\text{mol L}^{-1}$, $n = 93$), TIC ($272 \pm 12 \mu\text{mol L}^{-1}$, $n = 94$) and CO₂ ($45 \pm 3 \mu\text{mol L}^{-1}$, $n = 110$) concentrations (Fig. 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 $28 \pm 2 \mu\text{mol L}^{-1}$ ($n = 200$) and contributed less than 20 % of the TIC in this watershed (Fig. 2). We could not identify any clear seasonal pattern for POC, DOC, TIC and CO₂ concentrations in the four rivers of the Nam Theun watershed (Fig. 2).

As reported in Descloux et al. (2016), the average total water discharge in the reservoir is $238 \text{ m}^3 \text{ s}^{-1}$ ranging from $6 \text{ m}^3 \text{ s}^{-1}$ during the WD seasons to $2061 \text{ m}^3 \text{ s}^{-1}$ during the WW seasons. Carbon input to the reservoir as DOC,

POC and TIC ranged from $32.2 \pm 1.3 \text{ Gg C yr}^{-1}$ in 2010 to $46.2 \pm 1.5 \text{ Gg C yr}^{-1}$ in the wet year 2011 (Fig. 3). During the monitoring, TIC represented 60 to 70 % of the carbon inputs to the reservoir (Fig. 3).

3.2 Vertical profiles of temperature, O₂, pH, CO₂ and organic carbon in the reservoir water column

At the stations RES1–RES8, the typical vertical distributions of temperature, O₂, DOC, POC and CO₂ for the three seasons at various sampling stations are shown in Fig. 4. As already described in detail in Guérin et al. (2016), during the 4 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 stratifica-

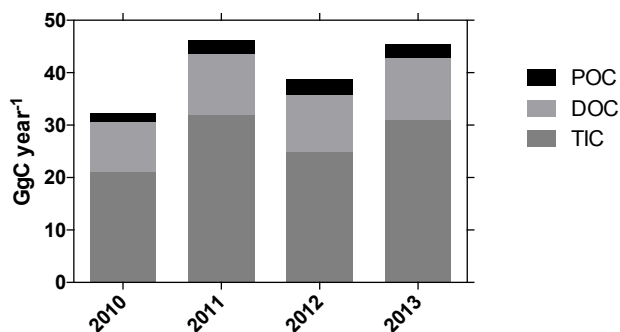


Figure 3. Total carbon inputs in the form of particulate organic carbon (POC), dissolved organic carbon (DOC) and total inorganic carbon (TIC) from the Nam Theun watershed to the Nam Theun 2 Reservoir for 4 distinct years after reservoir impoundment.

tion, the warm epilimnic waters are well oxygenated (> 80 % saturation), whereas the hypolimnion is anoxic (Fig. 4). Occasionally, sporadic and local destratification occurred during high water inflow in the WW season. During the CD season, temperature and O₂ decreased gradually with depth or O₂ concentration was constant from the surface to the bottom of the water column (Fig. 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 O₂ profiles from the surface to the bottom (Fig. 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 CO₂ 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, CO₂ concentrations increased with water depth and often showed a maximum gradient at or just below the thermocline (Fig. 4). For the years 2010 to 2013, the average CO₂ concentrations in the water column during the WD and WW seasons were always 50 % higher than in the CD season (Fig. 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 in DOC in the water column from year to year with average DOC concentrations of 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; Fig. 4). Since commissioning, O₂ 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 seasons (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. CO₂ 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). CO₂ 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 2 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 and temporal variations as described for the other stations.

3.3 Reservoir surface CO₂ concentration and diffusive fluxes

The reservoir surface CO₂ concentrations (*n* = 1067) ranged from 0.3 to 970 μmol L⁻¹ (Fig. 5a, b) and diffusive fluxes ranged from -40.4 up to 2694.9 mmol m⁻² d⁻¹ (Fig. 5c, d). Most of the dataset (85 % of all measurements) showed CO₂ 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 CO₂ 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

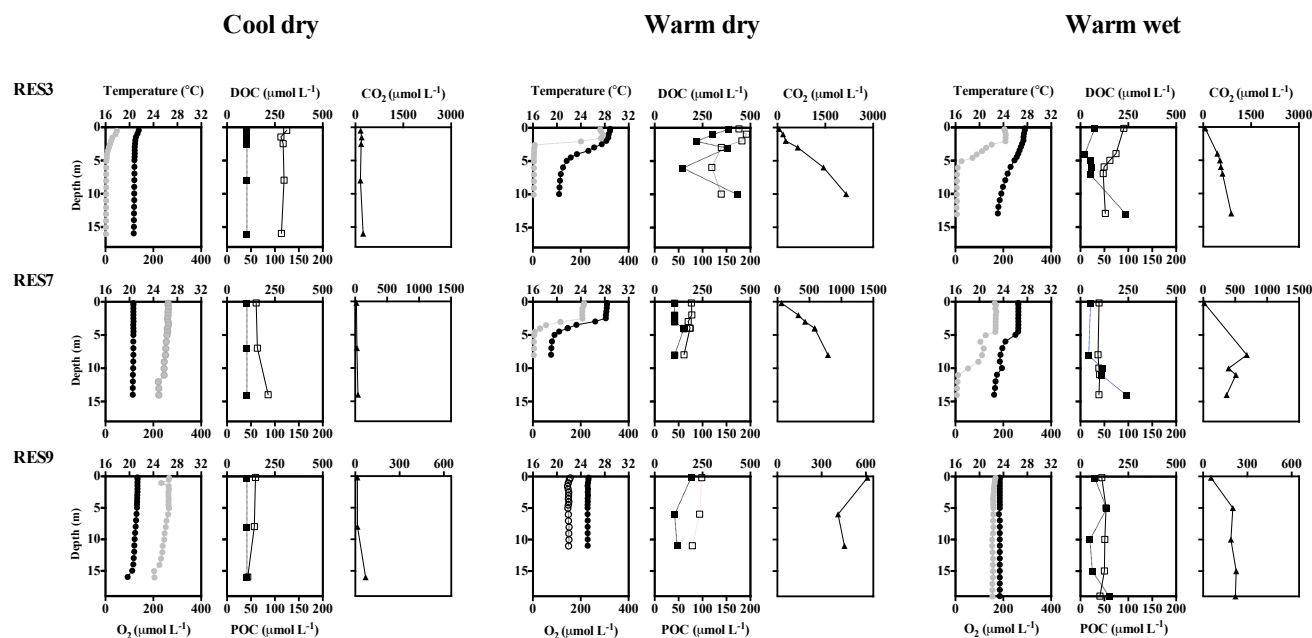


Figure 4. Temperature (grey solid circle) and oxygen (black solid circle), DOC (open square) and POC (solid square), and CO₂ (triangle) concentrations in the Nam Theun 2 Reservoir water column during the cool dry (CD), warm dry (WD) and warm wet (WW) seasons in 2011 at three stations (RES3, RES7 and RES9).

period, the highest concentration and fluxes were always observed in the WD season ($70 \pm 3 \mu\text{mol L}^{-1}$ and $90 \pm 9 \text{ mmol m}^{-2} \text{ d}^{-1}$), they decreased down to $51 \pm 3 \mu\text{mol L}^{-1}$ and $65 \pm 8 \text{ mmol m}^{-2} \text{ d}^{-1}$ in the WW and reached their minima in the CD season ($45 \pm 3 \mu\text{mol L}^{-1}$ and $22 \pm 2 \text{ mmol m}^{-2} \text{ d}^{-1}$) (Fig. 5a, c). In 2013, the reservoir was a net CO₂ sink from March to August ($-11 \pm 2 \text{ mmol m}^{-2} \text{ d}^{-1}$, $n = 96$) and emissions in the CD season were $66 \pm 9 \text{ mmol m}^{-2} \text{ d}^{-1}$ ($n = 41$) that is 3 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 CH₄ (Guérin et al., 2016). The average surface CO₂ concentrations at RES9 were 287 ± 350 and $184 \pm 234 \mu\text{mol L}^{-1}$ for the year 2010 and 2011, respectively that is 3- to 5-fold higher than the average at the other stations (Fig. 5b). In 2012, surface CO₂ concentrations at RES9 dropped down to $65 \pm 23 \mu\text{mol L}^{-1}$, 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 ($33 \pm 4 \mu\text{mol L}^{-1}$ in 2013). On an annual basis, the diffusive fluxes at RES9 decreased from an average of 745 ± 195 to $18 \pm 9 \text{ mmol m}^{-2} \text{ d}^{-1}$ between 2010 and 2013 (Fig. 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 diffu-

sive fluxes were then up to 17-fold higher than the average fluxes at the other stations for that same period (Fig. 5c, d).

Monthly emissions by diffusive fluxes varied by 2 orders of magnitude between 2009 and 2012. Superimposed on the general decrease in 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 (Fig. 5e). The annual diffusive CO₂ emission from the reservoir was $730.0 \pm 46.2 \text{ Gg}(\text{CO}_2) \text{ yr}^{-1}$ in 2009 and dropped down by a factor of 6 in 2013 ($118 \pm 11.5 \text{ Gg}(\text{CO}_2) \text{ yr}^{-1}$; Fig. 5f).

3.4 O₂, pH, organic carbon and CO₂ downstream of the reservoir

After the commissioning, immediately downstream of the power station (station TRC1), the average O₂ concentration was $174 \pm 58 \mu\text{mol L}^{-1}$, that is, $67 \pm 20\%$ saturation ($n = 189$) and pH was 6.55 ± 0.04 ($n = 234$). Further downstream, the O₂ concentration always increased and the O₂ 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 O₂ concentration was $237 \mu\text{mol L}^{-1}$, that is, 93% saturation ($n = 120$). There was no marked interannual change in the O₂ concentration. At DCH4, pH increased to 7.17 ± 0.04 ($n = 186$).

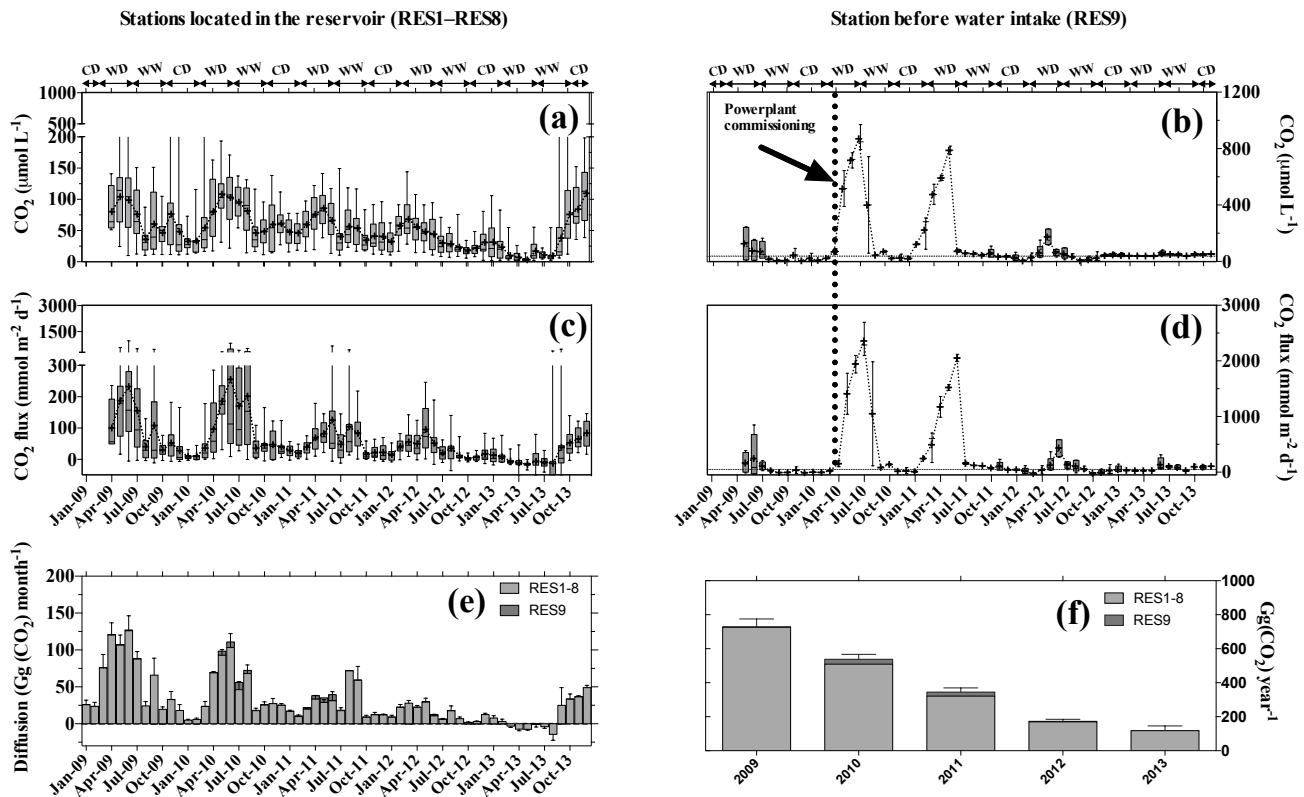


Figure 5. Monthly average CO₂ concentrations at the stations RES1–8 (a) and at the station RES9 (b), average diffusive fluxes at the stations RES1–8 (c) and at the station RES9 (d) and total monthly (e) and yearly (f) CO₂ emissions by diffusive fluxes from the Nam Theun 2 Reservoir (Lao PDR).

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

CO₂ 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 3 orders of magnitude, ranging from 1.4 to $856 \mu\text{mol L}^{-1}$ with an average of $153 \pm 14 \mu\text{mol L}^{-1}$ ($n = 199$). The CO₂ 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 CO₂ concentration decreased by a factor of 3 within a distance of 30 km during the WD and WW seasons (from 267 ± 34 to $90 \pm 10 \mu\text{mol L}^{-1}$ and from 235 ± 28 to $70 \pm 8 \mu\text{mol L}^{-1}$, respectively for WD and WW). In the CD season when CO₂ concentrations were lower, the decrease in concentra-

tion with distance from the dam was only by a factor of 2 (from 49 ± 8 to $30 \pm 4 \mu\text{mol L}^{-1}$). Between 2010 and 2013 for all stations in the downstream channel (TRC1 to DCH4), annual average CO₂ concentrations decreased by a factor of 7 from $182 \pm 9 \mu\text{mol L}^{-1}$ to $24 \pm 2 \mu\text{mol L}^{-1}$. On average, CO₂ concentration reached down to $56 \pm 5 \mu\text{mol L}^{-1}$ at DCH4, which is in the same order of magnitude as the concentrations found in the pristine Xe Bangfai River (XBF1, $60 \pm 2 \mu\text{mol L}^{-1}$, $n = 64$), Nam Kathang Noy River (NKT1, $35 \pm 3 \mu\text{mol L}^{-1}$, $n = 47$) and Nam Kathang Gnai River (NKT2, $82 \pm 10 \mu\text{mol L}^{-1}$, $n = 70$).

Immediately downstream of the Nakai Dam (NTH3) after the commissioning, the average O₂ concentration was $224 \mu\text{mol L}^{-1}$, that is 87% saturation ($n = 73$), and the concentration increased further downstream. pH was 6.84 ± 0.06 ($n = 166$). Average DOC concentration was $166 \pm 2 \mu\text{mol L}^{-1}$ ($n = 653$) and decreased from $197 \pm 4 \mu\text{mol L}^{-1}$ in 2010 ($n = 147$) to $162 \pm 3 \mu\text{mol L}^{-1}$ ($n = 127$) in 2013. The average POC concentration was $50 \pm 5 \mu\text{mol L}^{-1}$ ($n = 7$) and CO₂ concentration was $67 \pm 9 \mu\text{mol L}^{-1}$ ($n = 77$). The CO₂ concentration decreased by a factor of 2 ($40 \pm 5 \mu\text{mol L}^{-1}$, $n = 54$) within the next 10 km below the dam (down to NTH4, Fig. 1), where pH was

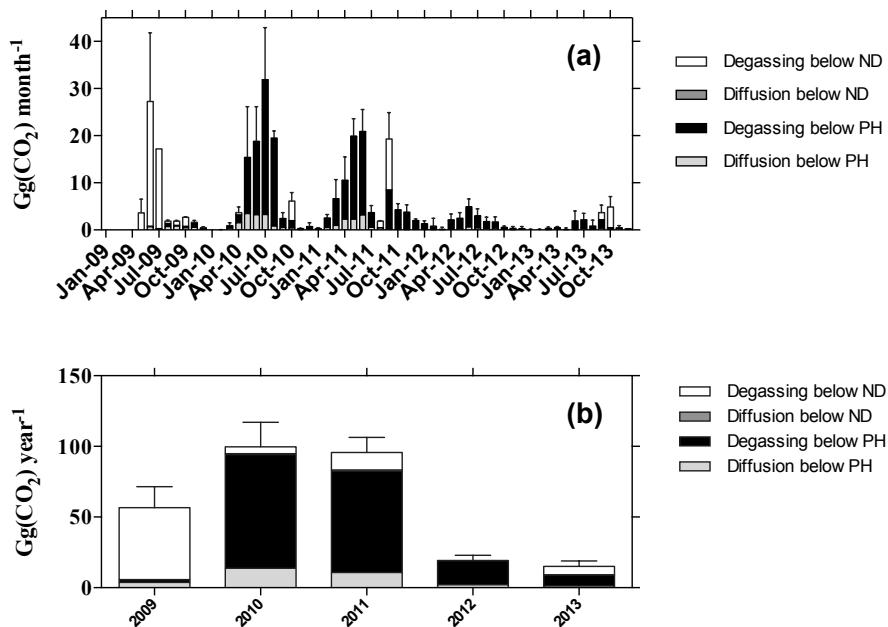


Figure 6. Diffusive fluxes and degassing below the powerhouse (PH) and the Nakai Dam (ND) on a monthly (a) and yearly basis (b) at the Nam Theun 2 Reservoir (Lao PDR). Note that degassing below ND includes spillway release (main contributor to 2009 and 2011 emissions below ND). Degassing below the powerhouse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

7.19 ± 0.06 ($n = 97$). At NTH4, the observed concentrations were in the same order of magnitude as the concentrations in the pristine rivers in the same watershed ($53 \pm 6 \mu\text{mol L}^{-1}$ at NPH1 in the Nam Phao River, $n = 59$).

3.5 CO₂ emissions downstream of the reservoir

After the commissioning, the annual average diffusive fluxes downstream of the powerhouse decreased from $482 \pm 603 \text{ mmol m}^{-2} \text{ d}^{-1}$ in the year 2010 (-32 – $33\,762 \text{ mmol m}^{-2} \text{ d}^{-1}$) to $32 \pm 8 \text{ mmol m}^{-2} \text{ d}^{-1}$ (-39 – $216 \text{ mmol m}^{-2} \text{ d}^{-1}$) in 2013 (not shown). They followed the same seasonal dynamics as the CO₂ concentrations and they decrease with the distance from the powerhouse. Total emissions by diffusion from the downstream channel decreased from $14 \pm 12 \text{ Gg(CO}_2\text{) yr}^{-1}$ in 2010 to $1.3 \pm 0.5 \text{ Gg(CO}_2\text{) yr}^{-1}$ in 2013 (Fig. 6a). Degassing in the whole downstream channel (including degassing below the turbines, the regulating pond and the aeration weir) reached up to $28.5 \text{ Gg(CO}_2\text{) month}^{-1}$ just after the commissioning of the reservoir when the water was released for the first time (Fig. 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 hypolimnetic waters were the most enriched in CO₂ (Fig. 6a). Total degassing decreased from $80 \pm 36 \text{ Gg(CO}_2\text{) yr}^{-1}$ in 2010 to $8 \pm 4 \text{ Gg(CO}_2\text{) yr}^{-1}$ in 2013 (Fig. 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 $0.48 \text{ Gg(CO}_2\text{) month}^{-1}$) is usually 10 times lower than degassing in the downstream channel because of (1) the low continuous water discharge at the Nakai Dam ($2 \text{ m}^3 \text{ s}^{-1}$) and (2) the withdrawal of the water from the reservoir epilimnion (Deshmukh et al., 2016; Fig. 6a). However, during the use of spillways for water-level regulation in the reservoir, degassing reached up to $26 \text{ Gg(CO}_2\text{) month}^{-1}$ in 2009 before the commissioning and 4 to $10 \text{ Gg(CO}_2\text{) month}^{-1}$ during the occasional uses in October 2010 and September 2011 (Fig. 6a). As determined from the longitudinal profiles of CO₂ 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 CH₄ (Deshmukh et al., 2016). The annual average diffusive CO₂ fluxes were 126 ± 137 and $288 \pm 346 \text{ mmol m}^{-2} \text{ d}^{-1}$ in 2010 and 2011, respectively. The annual average diffusive CO₂ flux was 1 order of magnitude lower in 2013 ($24 \pm 68 \text{ mmol m}^{-2} \text{ d}^{-1}$; not shown). The total emissions by diffusion and degassing resulting from these fluxes ranged between $5.5 \pm 0.1 \text{ Gg(CO}_2\text{) yr}^{-1}$ in 2010 and $0.14 \pm 0.06 \text{ Gg(CO}_2\text{) yr}^{-1}$ in 2013 (Fig. 6b).

On a yearly basis, emissions downstream of NT2R decreased from 99.7 ± 25.3 to $15.0 \pm 6.5 \text{ Gg(CO}_2\text{) yr}^{-1}$ between 2010 and 2013 (Fig. 6b). Before the reservoir com-

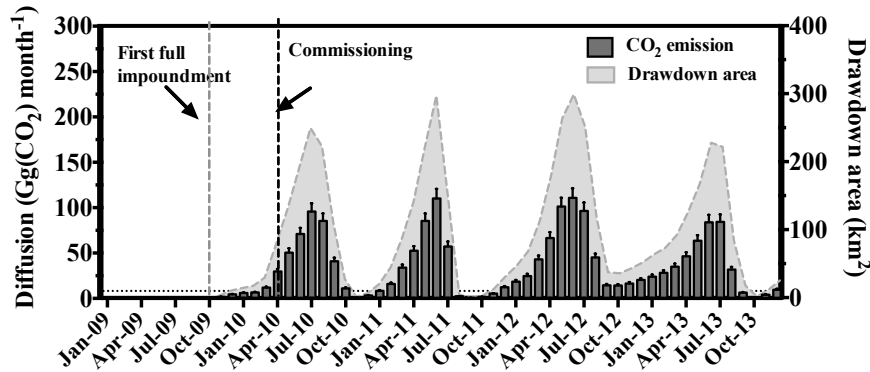


Figure 7. Monthly emissions from the drawdown area and variation in the area of the drawdown of the Nam Theun 2 Reservoir (Lao PDR).

missioning 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 CO₂ bubbling

The CO₂ content in the sampled bubbles was 0.29 ± 0.37 % ($n = 2334$). On average, the CO₂ bubbling was 0.16 ± 0.24 mmol m⁻² d⁻¹ (0 – 2.8 mmol m⁻² d⁻¹) for depths shallower than 16 m. Considering the water surface variations, the monthly ebullitive CO₂ emissions ranged from 0.04 ± 0.06 to 0.11 ± 0.16 Gg(CO₂) month⁻¹. CO₂ bubbling was constant around 1.1 ± 2.2 Gg(CO₂) yr⁻¹ throughout the monitoring.

3.7 CO₂ 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 the NNR (Nam Nien River) 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 CO₂ 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 con-

tent ($p = 0.0452$). Since we did not observe significant spatial variations related to topography, humidity or temperature that could have been considered for refined 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 3 orders of magnitude. Since a constant CO₂ emission is accounted for, the seasonal pattern of CO₂ emission from the drawdown mimics the variation of the surface of that area (Fig. 7). Monthly CO₂ emissions have reached up to 110.8 ± 10.7 Gg(CO₂) 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(CO₂) month⁻¹ at the end of the WW season when drawdown area reached its minimum (Fig. 7). Around 80–90 % of the annual emissions occurred within 4–6 months of the transition period between the WD and WW seasons (Fig. 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(CO₂) yr⁻¹) and the highest emissions during the dry year 2012 (572 ± 20 Gg(CO₂) yr⁻¹). On average from 2009 to 2013, emissions from the drawdown area were 431 ± 42 Gg(CO₂) yr⁻¹.

4 Discussion

4.1 CO₂ dynamics in the NT2R water column and downstream rivers

The dynamics of CO₂ in the NT2R is highly dependent on the hydrology and hydrodynamics of the reservoir as it has already been described for CH₄ (Guérin et al., 2016). During the warm seasons (WD and WW) when the water column is thermally stratified, the vertical profiles of CO₂ concentration in the water column are similar to profiles obtained in other tropical or subtropical reservoirs (Abril et al., 2005; Guérin et al., 2006; Chanudet et al., 2011; Kemenes et al., 2011), but also boreal reservoirs (Demarty et al., 2011). The

high concentrations measured in the hypolimnion suggest that the main source of CO₂ is located at the bottom and very likely in the flooded soils, vegetation and sediments, whereas the decrease in CO₂ 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; Barros et al., 2011; Chanudet et al., 2011; Teodoru et al., 2011). In the CD season, after the reservoir overturn, the average CO₂ concentration in the reservoir water column decreases sharply (by 50 % on average) and CO₂ concentration increases regularly from the surface to the bottom of the water column. However, no CO₂ burst was observed at the beginning of the CD season, evidence that reservoir overturn has only a moderate impact on CO₂ emissions. This assumption is reinforced by the fact that during the same sampling, hot moments of CH₄ emissions that should have occurred at the same time were captured (Guérin et al., 2016). As observed in most tropical and subtropical reservoirs, the higher concentrations were observed during the warm seasons due to long residence time of water and warmer conditions enhancing CO₂ build-up (Abril et al., 2005; Chanudet et al., 2011; Kemenes et al., 2011), whereas the lowest were found after reservoir overturn when the water outgassed (Chanudet et al., 2011). A significant shift in the carbon biogeochemical cycling occurred in the reservoir in 2013 with the reservoir water surface becoming a CO₂ sink during the WD season and the beginning of the WW season (from March to August). Although no major change was observed in nutrient concentrations, the number of phytoplanktonic cells was 50 % higher in 2013 than 2012 (Maud Cottet, personal communication, 2017) indicating that primary production was significantly enhanced in 2013. Despite the fact that the reservoir was a sink for the 6 months when CO₂ emissions are usually the highest of the year, annual CO₂ emissions at the surface of the reservoir were only 50 % lower in 2013 than in 2012. In 2013, CO₂ was mainly emitted in the CD after the period of high biological productivity suggesting that the degradation of autochthonous OM fuels CO₂ emissions.

The maximum concentration and the highest CO₂ stock in the water column highly depend on the age of the reservoir. In the NT2R, average CO₂ concentration was 3 times higher in 2010 than in 2013 and the maximum concentrations in 2010 was almost 2 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 CO₂ concentrations in the NT2R are in the same range as concentrations in other older reservoirs in the tropics or the subtropics (Abril et al., 2005; Guérin et al., 2006; Chanudet et al., 2011; Kemenes et al., 2011). This decrease

during the first 4 years after impoundment is very consistent with the decrease in the CO₂ 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 a multi-site study (Barros et al., 2011).

Disregarding the station RES9 located at the water intake, no significant spatial variation in CO₂ surface concentrations was found despite very significant differences in hypolimnic concentration between stations located upstream of the Nakai Dam (RES1, 2 and 3) and stations located in areas close to the three main tributaries (RES6, 7 and 8). The average hypolimnic concentrations at the stations RES1–3 were 2 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 Sect. 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 (Fig. 1). Therefore, the water renewal in the RES6–9 area is high and CO₂ accumulates less in the water column confirming the importance of the reservoir hydrology on the spatial variability in dissolved gases in reservoirs (Pacheco et al., 2015; Guérin et al., 2016).

As found for CH₄, the main factor influencing the spatial variability of CO₂ in the water column is the vertical mixing of the water column induced by the water intake located close to RES9 (Deshmukh et al., 2016; Guérin et al., 2016). The design of the water intake enhances horizontal water current velocities and vertical mixing which lead to the transport of bottom waters to the surface. As a consequence, surface concentrations at RES9 were up to 30 times higher than at other stations in 2010 and 2011 (Fig. 5b). With the significant decrease in concentrations in 2012 and 2013, the difference with other stations dropped to a factor of 4. These maximum surface concentrations at RES9 are up to 10 times higher than concentrations found in other tropical reservoirs in South America (Abril et al., 2005; Guérin et al., 2006; Kemenes et al., 2011) and Lao PDR (Chanudet et al., 2011) showing that, as for CH₄, CO₂ emissions can be enhanced upstream of water intakes or dams.

Downstream of the reservoir in the Nam Theun River or the artificial channel, CO₂ concentrations follow the same seasonality as in the reservoir. Concentrations peak in June–July at the transition between the WD and WW seasons, and reach their minima in the CD season. Downstream of the Nakai Dam, the concentrations are twice lower than downstream of the powerhouse since mostly epilimnic water from the RES1 station is transferred downstream of the dam. Within less than 10 km further downstream, concentrations are not significantly different than in pristine rivers of

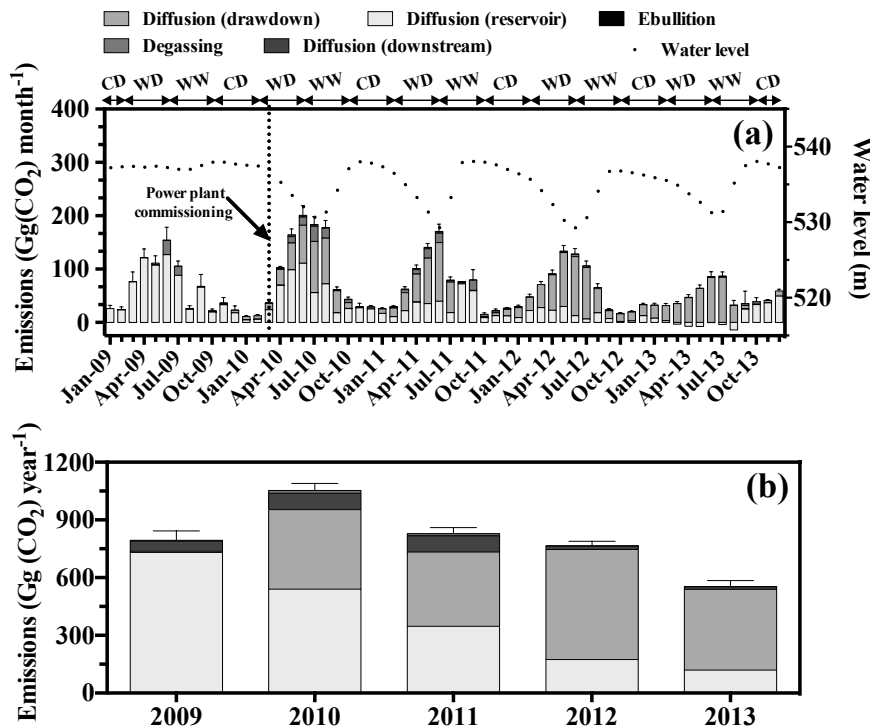


Figure 8. Monthly (a) and yearly (b) average of the total emissions from the Nam Theun 2 Reservoir by diffusion at the reservoir surface, diffusion from the drawdown area, ebullition, degassing and diffusion from the Nam Theun River and artificial channel at the Nam Theun 2 Reservoir (Lao PDR). In panel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

the watershed. Downstream of the powerhouse, CO₂ concentrations in 2010 were in the same order of magnitude as in 10–20 year-old reservoirs in South America flooding tropical forest (Abril et al., 2005; Guérin et al., 2006; Kemenes et al., 2011), whereas 4 years after impoundment CO₂ concentrations were 2 times lower than in 20–30 year-old reservoirs in Lao PDR (Chanudet et al., 2011). We hypothesize that the low CO₂ 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 CH₄ (Deshmukh et al., 2016; Guérin et al., 2016).

4.2 Total CO₂ emissions from the Nam Theun 2 Reservoir

From 2009 to 2013, total CO₂ emissions from NT2R show the same seasonal pattern (Fig. 8a). The lowest total emissions occur in the CD season while the highest emissions occur at the transition between the WD and WW seasons, when emissions by all individual pathways reach their maximum. From 2010 to 2013, emissions at the transition between the WD and 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.

CO₂ bubbling follows the same seasonal variations, being triggered by water level and concomitant hydrostatic decrease as for CH₄ (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 CO₂ emission by bubbling, as also observed in temperate reservoirs (Bevelhimer et al., 2016), is attributed to the higher solubility of CO₂ in water than CH₄ which leads to the solubilization of the majority of CO₂ as free CO₂ 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 Fig. 8a). As for CH₄ at NT2R (Deshmukh et al., 2016), the low downstream emissions are attributed to the significant degassing at the water intake (station RES9)

Table 3. CO₂ emissions (in Gg CO₂ year⁻¹) from the Nam Theun 2 Reservoir (Lao PDR) for the first 5 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

before the water reach the turbines and to the flush of CO₂ due to the reservoir overturn in the CD season.

Emissions by diffusive fluxes at the surface of the reservoir increased by a factor of 2 by the end of the WD season (Fig. 5a) compared to the CD season from 2009 to 2012. The average CO₂ emissions in 2009 and 2010 and to a lesser extend 2011 are in the same range as emissions from the Petit Saut Reservoir during the first 5 years after impoundment (Abril et al., 2005), and in the upper range of average CO₂ 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; Tadonléléké 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; Xiao et al., 2013; Zhao 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 the CD season in 2011 and 2012 are likely to be originated from additional autochthonous OM. We hypothesize that the significantly higher CO₂ emissions in the WD season result from the increase in the water residence time that favour CO₂ accumulation in the water column (Abril et al., 2005) and the increase in temperature that enhance aerobic and anaerobic degradation of OM and the production of CO₂ (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 (Fig. 8a), highlighting the very significant increase in CO₂ emissions from May to July every year, disregarding the year 2013.

This first estimation of the CO₂ emission from the drawdown area to the total emission from a reservoir reveals that

with a contribution ranging from 40 to more than 75 %, it could be a major CO₂ pathway to the atmosphere. These results from the NT2R cannot be generalized to all reservoirs since its contribution is tightly linked to the very large water-level variations and large surface area of the drawdown area (up to 320 km², Fig. 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 6 times higher than those fluxes in 2013 making the soils in the area of influence of the reservoir a hotspot for CO₂ emissions compared 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 km²), Samuel (~ 280 km²), Balbina (~ 220 km²) or The Three Gorges Reservoir (~ 400 km²) 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 to 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 (Feilix-Faure et al., 2017). The ecosystems of the seasonally flooded area are therefore significantly modified and CO₂ emissions from the drawdown must be accounted for in total gross emissions from reservoirs. Although drawdown emissions cannot be neglected in terms of gross CO₂ exchange, the emissions resulting from the soil respiration are currently comparable to pristine emissions (Table 2) and the impact of these areas in terms of net emissions requires further specific studies in these over-

looked ecosystems (Prairie et al., 2018). So far, we cannot predict future evolution of CO₂ emissions in this area based on the available data. The consequence of the flooding on the respiration rate of these soils may lead to a decrease in emissions with time or a stabilization (see next section). Therefore, the net contribution of the drawdown zone to emissions from the reservoir remains unclear and specifically requires research on soil OM dynamics and would also require the inclusion of the vegetation dynamics when present.

This is the first comprehensive quantification of CO₂ emissions from a reservoir where all known CO₂ pathways to the atmosphere were taken into account at one of the best spatial and temporal resolutions reported in the literature. We showed that downstream emissions and emissions around the water intake are not negligible (~ 10 % overall) and that the overlooked drawdown area in CO₂ studies could be the main emission pathway of CO₂ to the atmosphere. Overall, this study highlights that global estimate of CO₂ emissions from reservoirs are underestimated so far since relevant pathways like drawdown emissions in flat or shallow reservoirs with large water-level variations and downstream emissions in thermally stratified reservoirs are missing in most site-specific studies used for extrapolations (Deemer et al., 2016; Barros et al., 2011).

4.3 Source of organic matter fuelling the reservoir CO₂ emissions

In tropical reservoirs, the decrease in the CO₂ concentration in the water column and subsequent emissions with the age of the reservoir (Fig. 8b) is supposed to result from the decrease in the aerobic and anaerobic mineralization rate due to the exhaustion of labile OM from the pool of soil and vegetation that was flooded during impoundment (Abril et al., 2005; Guérin et al., 2008). In boreal reservoirs, the decrease in benthic CO₂ production is sharp and after 3–5 years, most of the CO₂ production appears to be pelagic and is supposed not to result from the flooded OM (Teodoru et al., 2011; Brothers et al., 2012). The total CO₂ emissions were 9 and 3 times higher than the carbon inputs from the watershed to the NT2R in 2010 (32 Gg C yr⁻¹) and 2013 (45 Gg C yr⁻¹), respectively (Fig. 3 and Table 3). It has to be noted that interannual variations in carbon inputs to the NT2R (Fig. 3) are not correlated with the regular decrease in total CO₂ emissions from year to year (Fig. 8b). It is therefore unlikely that most of CO₂ emissions result from the mineralization of allochthonous OM but rather from the contribution of the flooded carbon pool (soil and vegetation), which 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 de-

crease in emissions in NT2R than at Petit Saut. This sharp decrease in 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 (Abril et al., 2005; Guérin et al., 2008), that external sources of carbon are not sufficient to fuel the CO₂ emissions from the NT2R and we attribute the decrease in 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 subtropical NT2R, CO₂ 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 CO₂ 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 CO₂ concentration in the CD season is 50 % lower than in the warm seasons, we suggest that CO₂ is mostly produced in the sediment and flooded soils and vegetation. Disregarding the station RES9 located at the water intake, significant spatial variation in CO₂ 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. In the long run, the atmospheric carbon sink associated with the pristine vegetation dynamics has been lost, but as a consequence the loss of this vegetation might reduce labile OM inputs. In addition, the water-level variations erode the soil and OM is transferred to the reservoir and ultimately to the sediments or downstream (Feilix-Faure et al., 2017). Those carbon losses should have resulted in or should result in the future in a decrease in CO₂ emissions from the drawdown. The stability of emissions throughout our 4-year surveys in the drawdown area suggests that a 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 streams in logged riparian areas (Sabater et al., 2000) could supply labile OM to the system and favour a 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 mineralization of different pools of OM than those that would have been otherwise degraded 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 CO₂ emissions 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 soil organic matter 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 characterization 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 OM within a few years does not contribute significantly to emissions (Brothers et al., 2012). In addition to a strong temperature effect on mineralization 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 these two distinct climatic areas.

5 Conclusions

We presented the first comprehensive estimation of CO₂ emissions from a subtropical reservoir starting less than a year after reservoir impoundment and lasting 4.5 years. This estimation includes all known pathways to the atmosphere: emissions from the reservoir surface, downstream emissions and emissions from the drawdown area.

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

The smooth decrease in total emissions over the years coupled with the fact that the incoming flux of carbon from the watershed to the reservoir represents less than a third of the total emissions, are a strong indication that the flooded pool of OM 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 CO₂ emissions from the drawdown area represented 40–75% of the total emissions from the

NT2R and they occur within a few months during low water-level seasons. The soil OM from these areas undergoes anaerobic degradation and fuels the reservoir water column with CO₂ during the wet season. In the dry season, the soil loses CO₂ directly to the atmosphere while undergoing both aerobic and anaerobic mineralization 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 mineralization of stabilized soil organic matter 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, 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.

Data availability. Datasets are property of EDF, NTPC and Paul Sabatier University and are not public, but could be available on request (frederic.guerin@ird.fr).

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